Modeling of Fabric Impact with High-Speed Imaging and Nickel-Chromium Wires Validation

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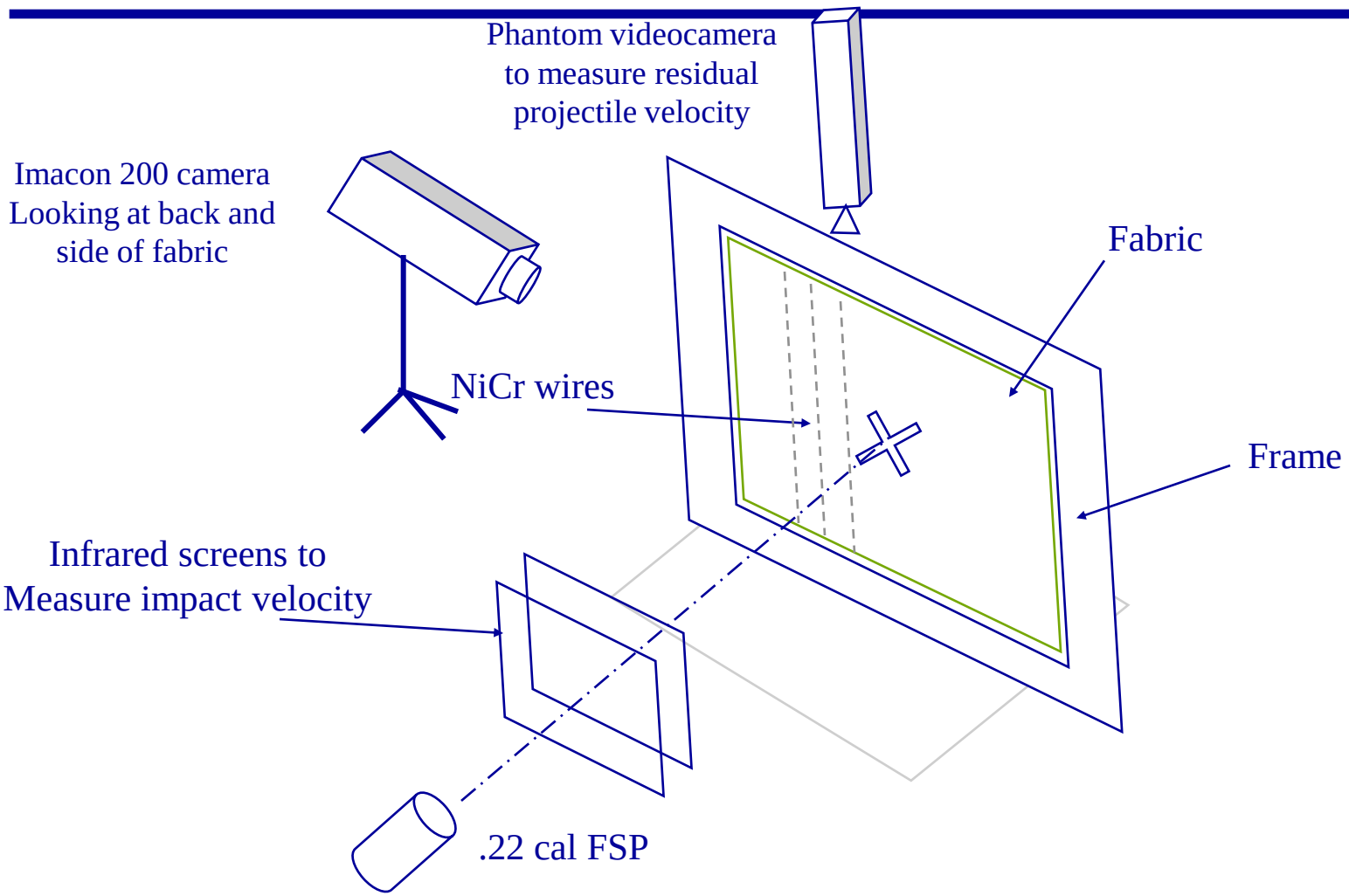
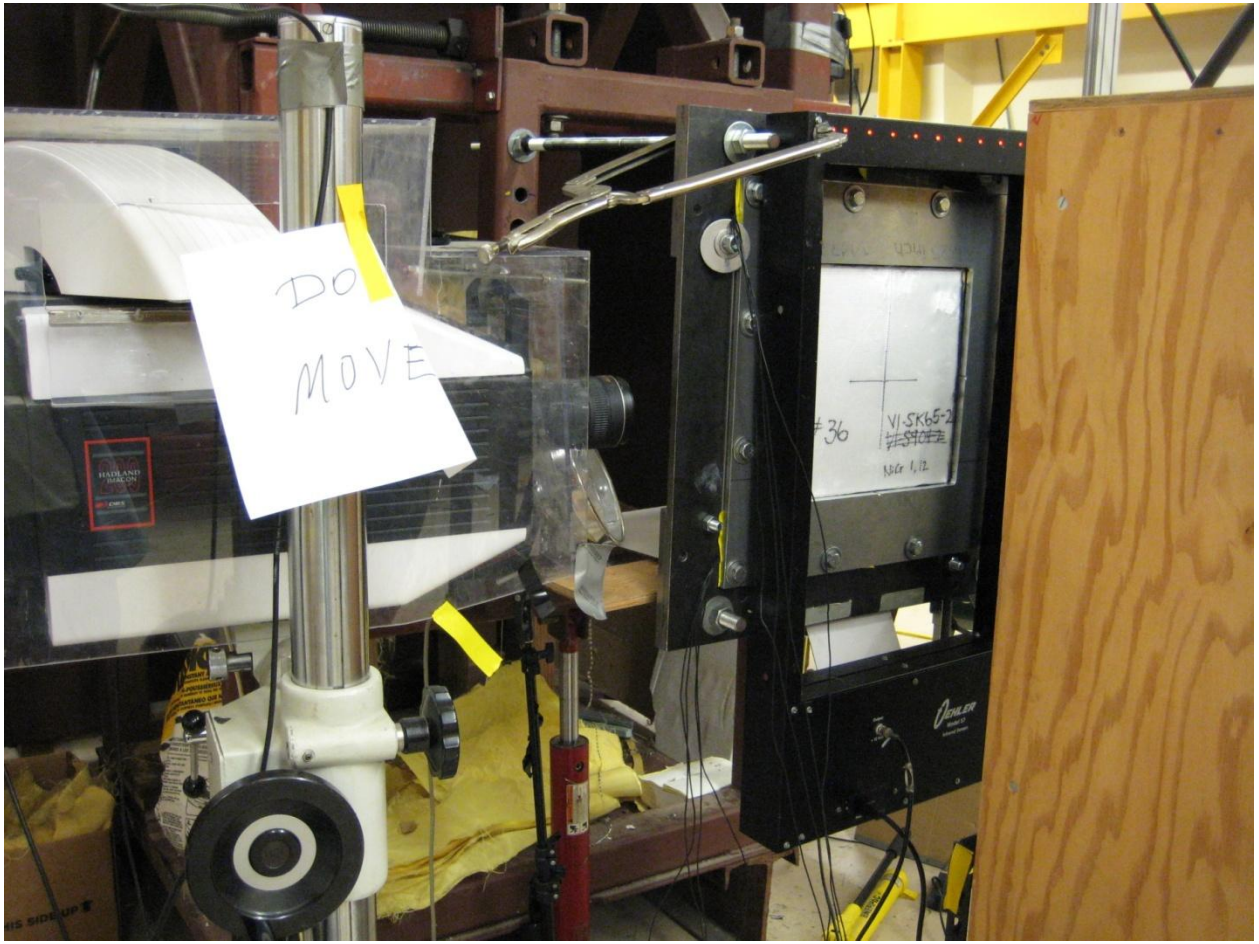
Outline

- Tests set-up and diagnostics:
  - Imacon Camera.
  - Phantom Camera.
- Computations with LS-DYNA and multi-pronged validation (single yarn, single layer, multi-layer and V50).
- Principles, main results and validation of Nickel-Chromium wire technique.

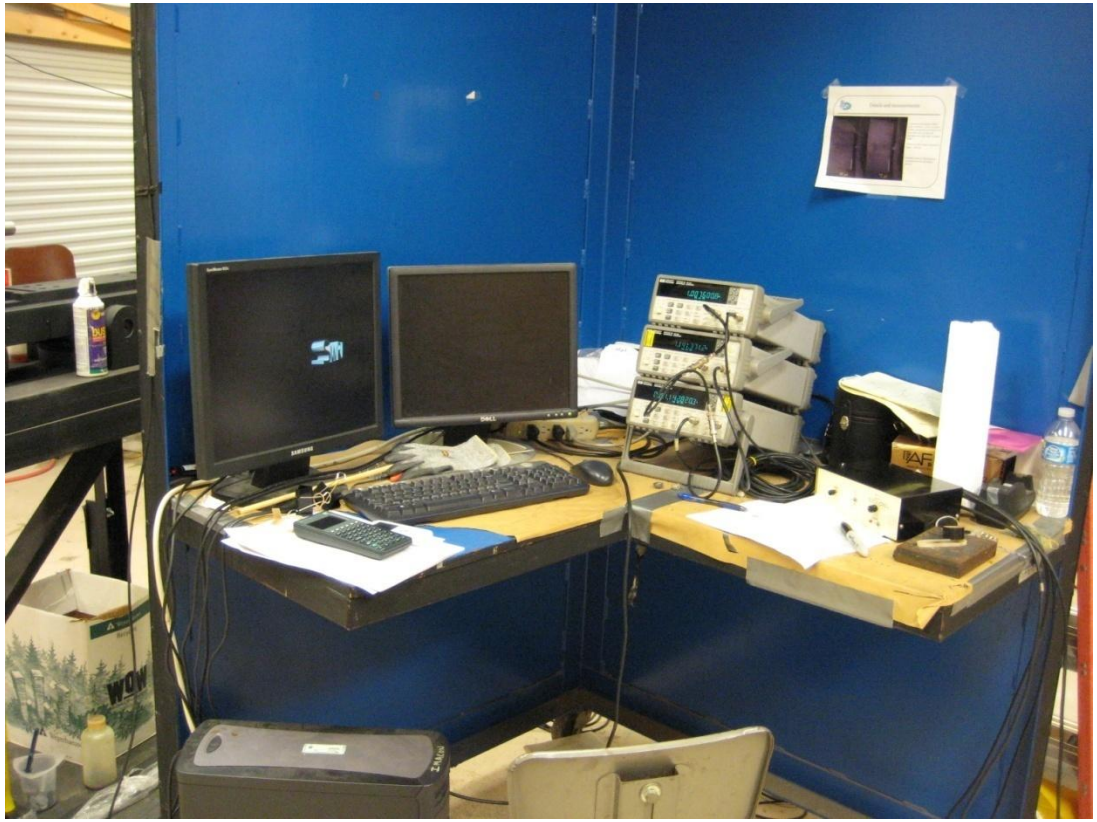
Test set-up: fabric with NiCr Wire



Test set-up



Test set-up



Diagnostics

- Imacon 200
  - 16 frames at a maximum rate of one every five nanoseconds. The resolution is 1200 980 pixels.
  - Used to watch the back of the target (sideways) during the first 50-80 μs at a rate of one frame every 5 μs. Exposure was 800 ns. The area seen was around 6 6 cm^2 (2.4 2.4 in^2) .
  - Provides early time position (and speed) of the transverse wave and the apex of the pyramid, time of penetration of last layer.
- Phantom V7
  - Provides hundreds of images of back of target, used at one frame every 100 μs. Resolution 800 240.
  - Gives residual velocity (and shape) of projectile, late time deflection of target, late time base of pyramid.

Materials

Fabric	Denier	Yarns per inch	Areal Density of one layer (kg/m^2)
Kev KM2 S5705	850	31	0.252
Kev KM2 S5706	600	34	0.186
Dyneema SK-65	792	w: 20, f: 15	0.126
PBO	500	24	0.113

The projectiles used were the .30 in. cal FSP (44 grain) and the .22 in. cal FSP (17 grain).

Numerical validation

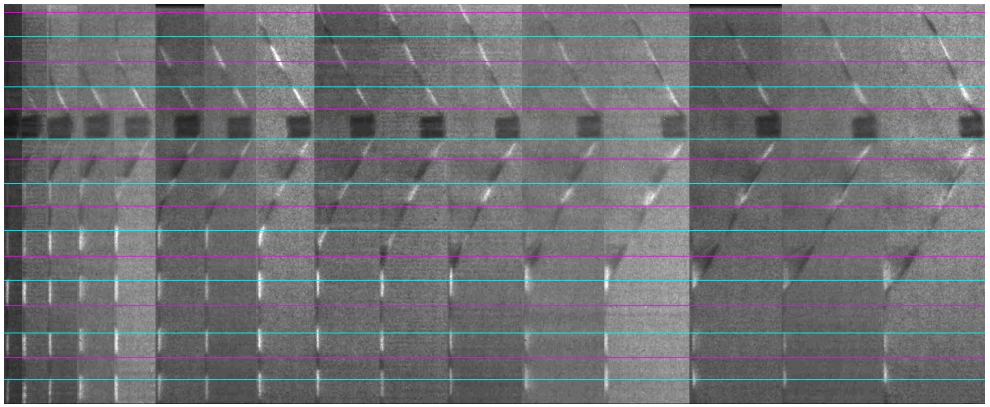
- Numerical validation was performed in various ways, providing great confidence on the model:
  - Single yarn impact.
  - Single layer impact.
  - Multi-layer tests.
  - Ballistic limit comparison.
  - NiCr wire comparison.

Single Yarn Impact Validation

Smith theory on transverse impact on single yarns

$$V = c\sqrt{\varepsilon(2\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon)}$$

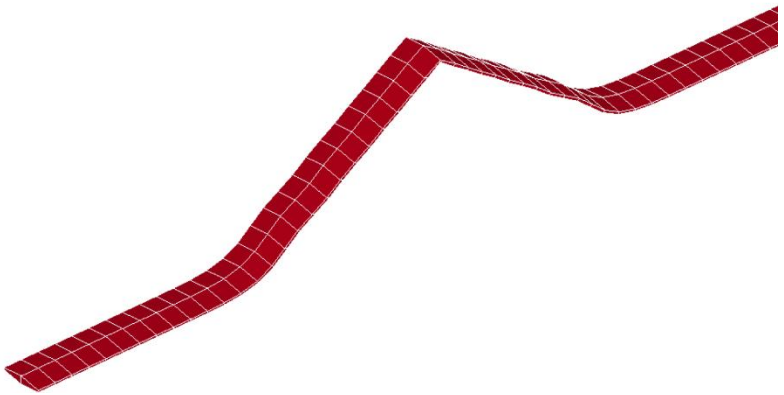
$$U = c\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon$$



Yarn Material	Density (g/cc)	Sound Speed (km/s)	Strength (GPa)	Theor. Critical Velocity (m/s)
KM2 S5705	1.44	7.45	3.4	945
Dyneema SK-65	0.97	9.89	3.42	1110
PBO	1.56	10.7	5.8	1108

Single Yarn Impact Validation

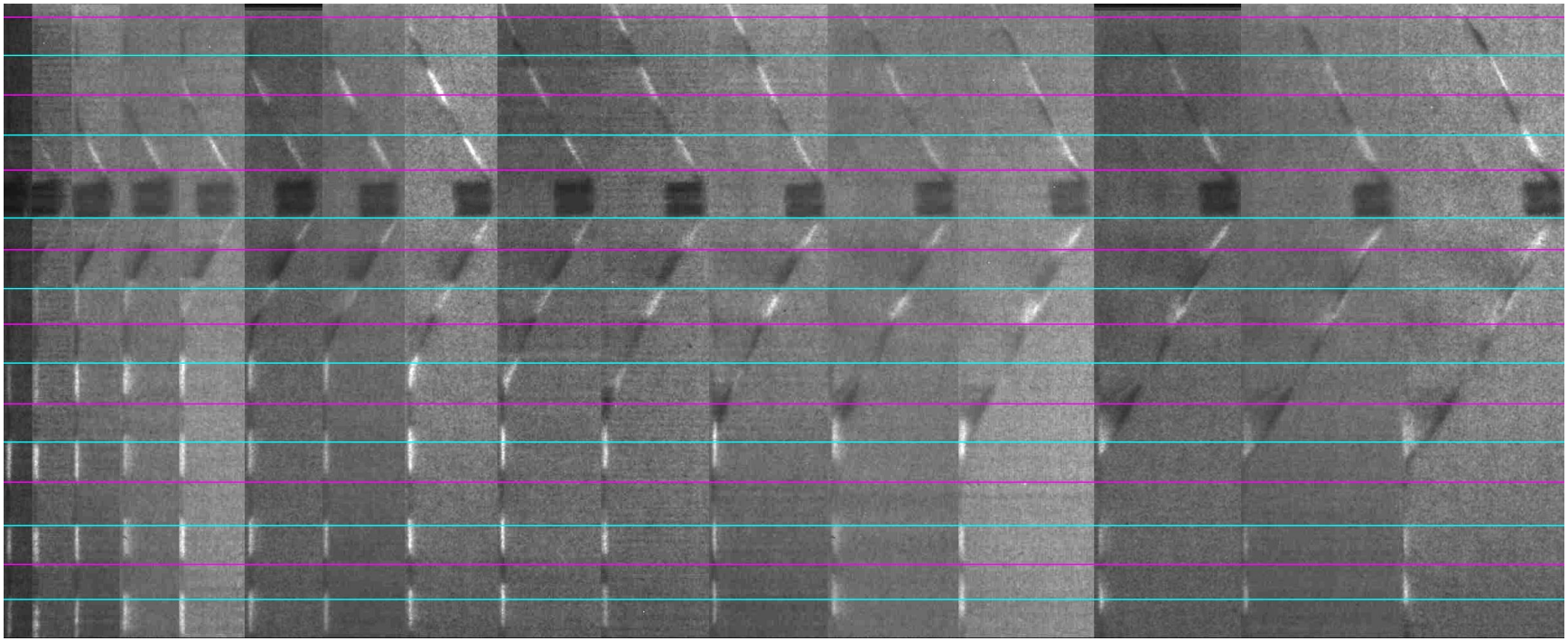
Validation performed on theoretical transverse wave velocity and not on theoretical critical velocity



Yarn Material	Impact vel. (m/s)	Theor.Transv. wave vel. (m/s)	Exp. Transv. wave vel. (m/s)	LS-DYNA Transv. wave vel. (m/s)
KM2 S5705	480	851	880	880
Dyneema SK-65	480	954	900	950
PBO	520	1033	1040	1060

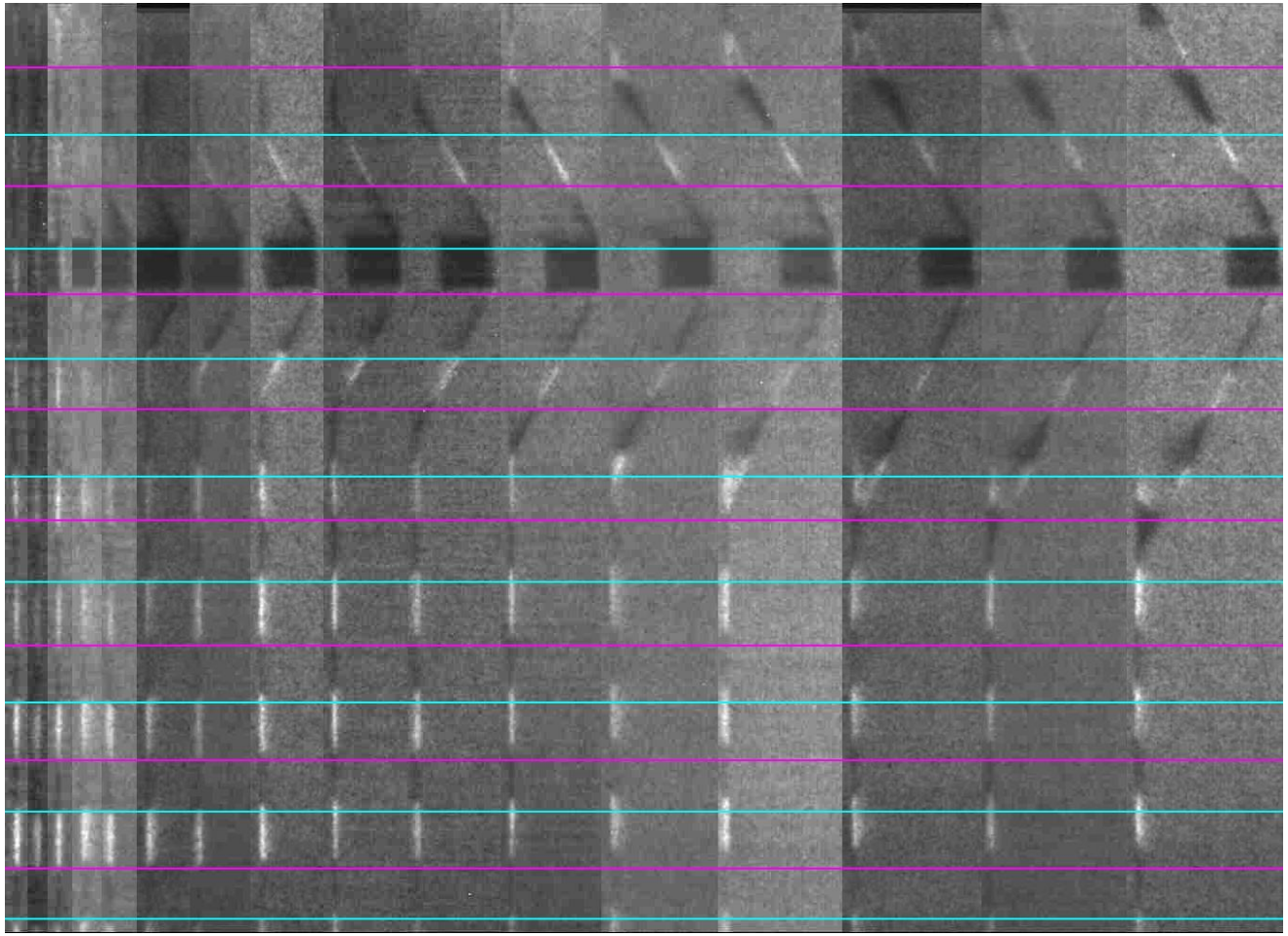
Material	Density (g/cm^3)	E_a (GPa)	E_b (GPa)	E_c (GPa)	ν	G (GPa)	σ_u (GPa)
KM2 S5705	1.44	80	8.0	8.0	0	0.8	3.4
Dyneema SK-65	0.97	95	9.5	9.5	0	0.95	3.42
PBO	1.56	180	18	18	0	1.8	5.8

Yarn 03 – Dyneema – 477m/s
5 us per frame



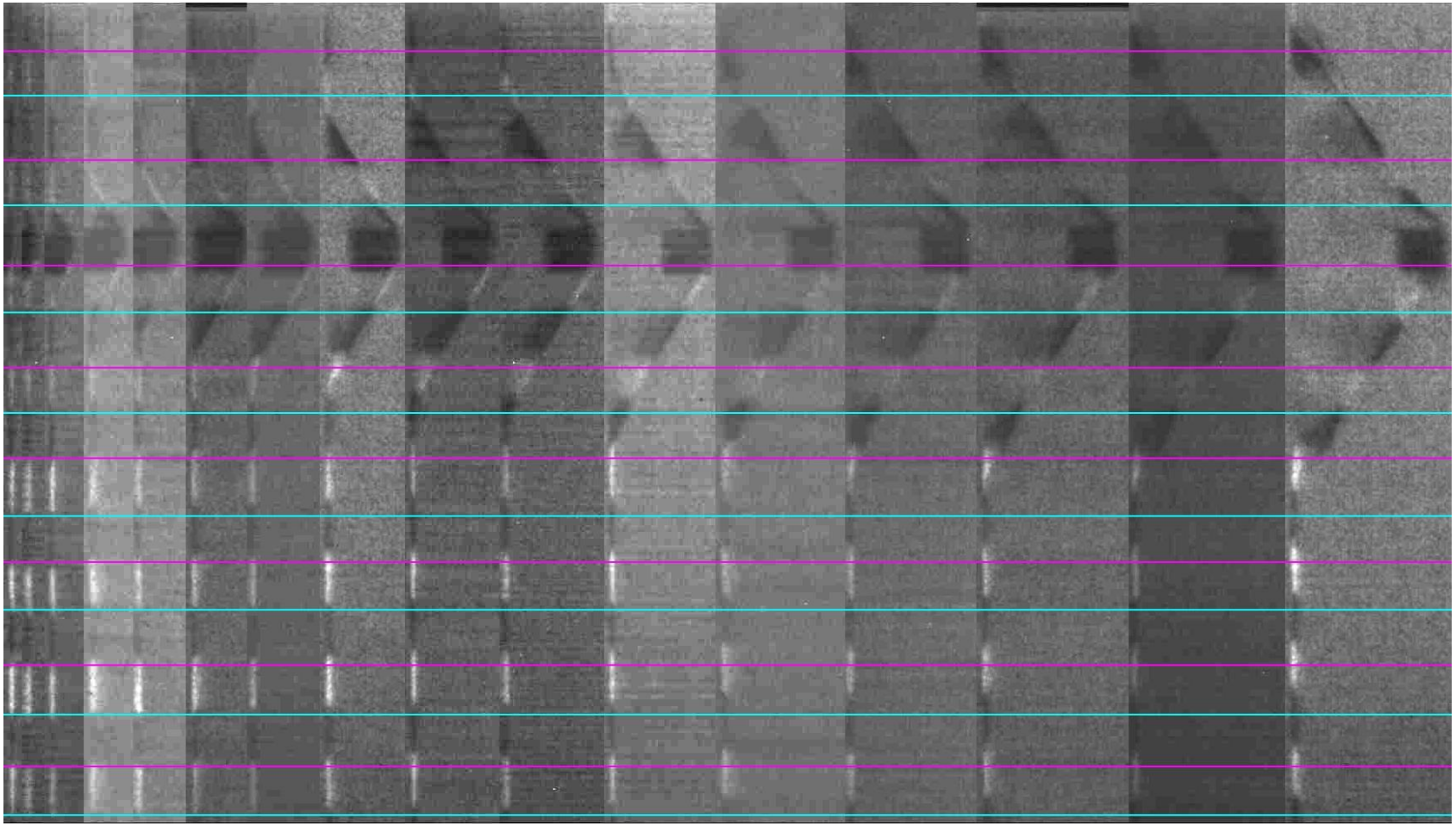
No failure

Yarn 06 – Dyneema – 474m/s
4 us per frame



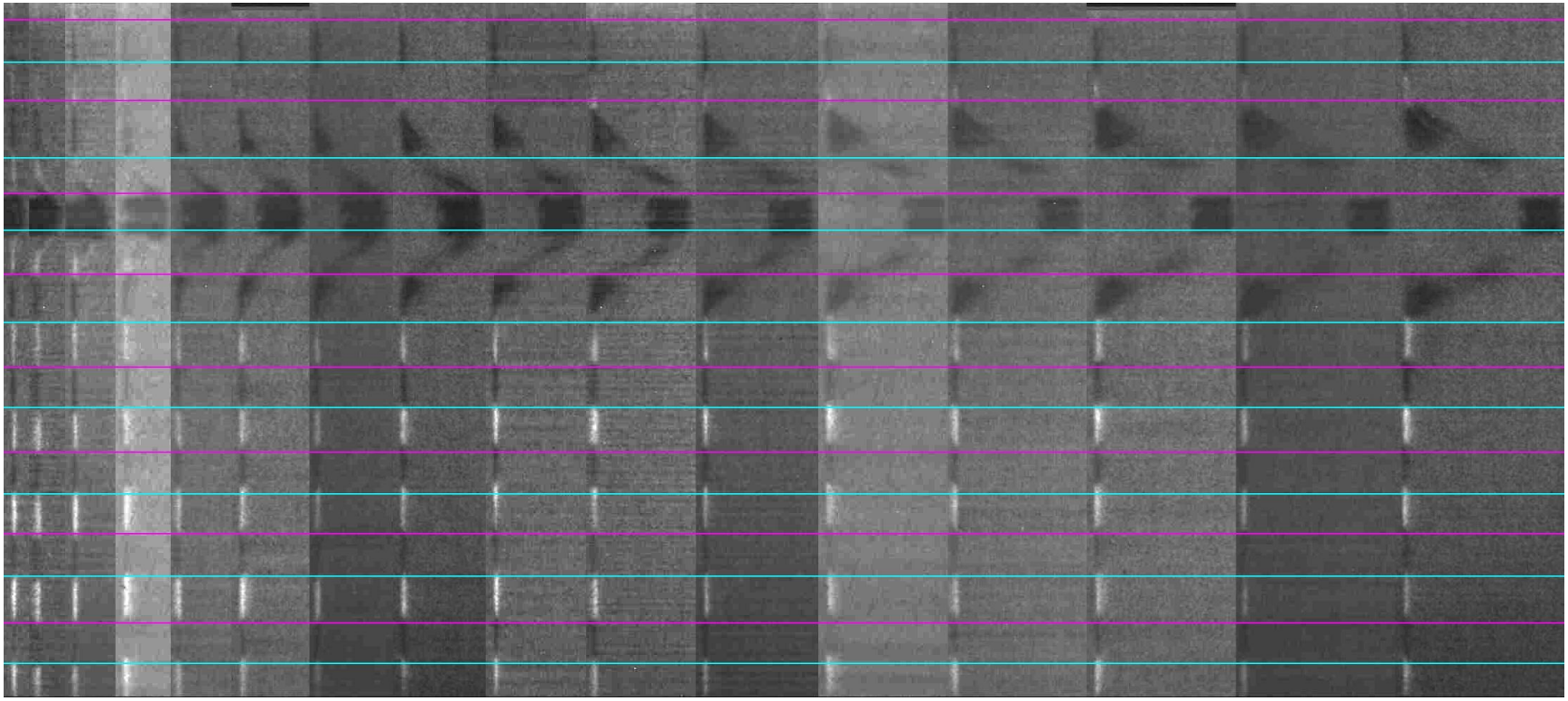
No failure

Yarn 12 – Dyneema – 517m/s
4 us per frame



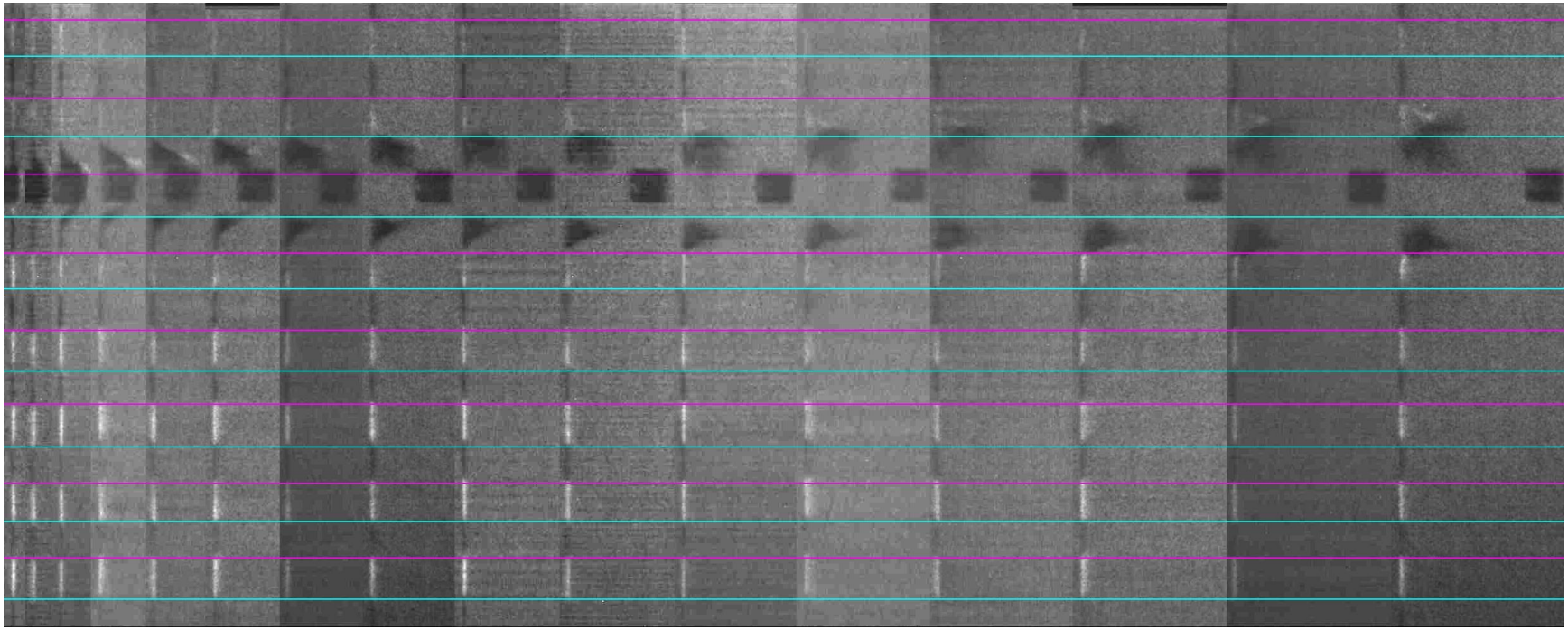
No failure

Yarn 11 – Dyneema – 583m/s
4 us per frame



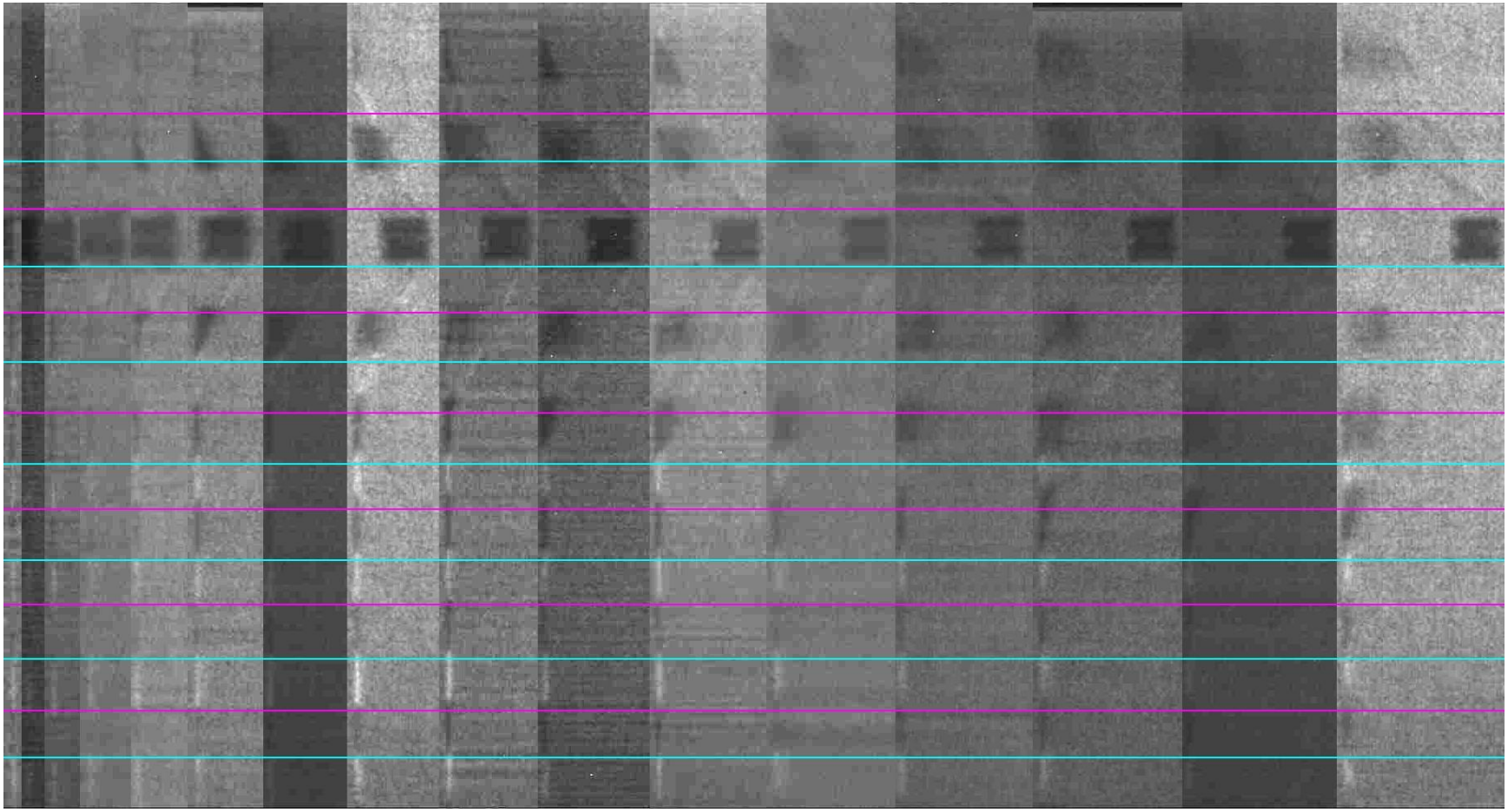
Immediate failure

Yarn 09 – Dyneema – 672m/s
4 us per frame



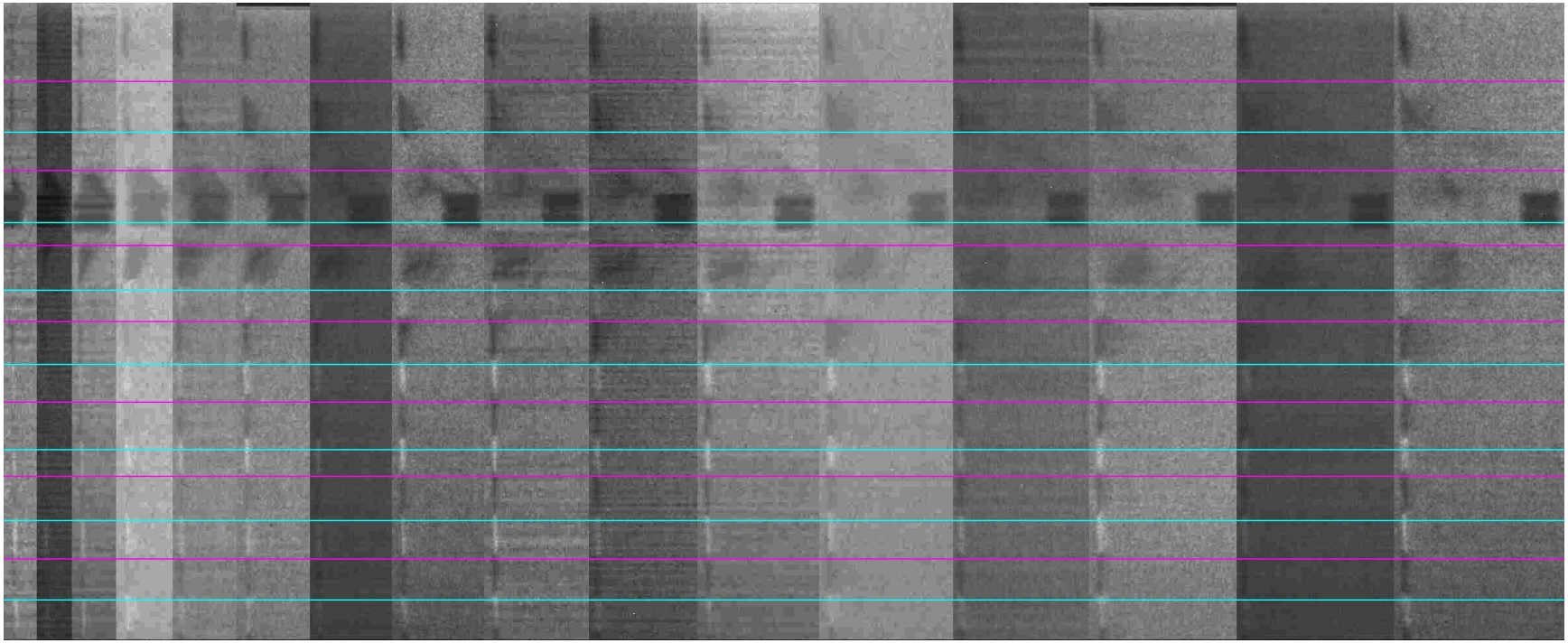
Immediate failure

Yarn 13 – PBO – 523m/s
4 us per frame



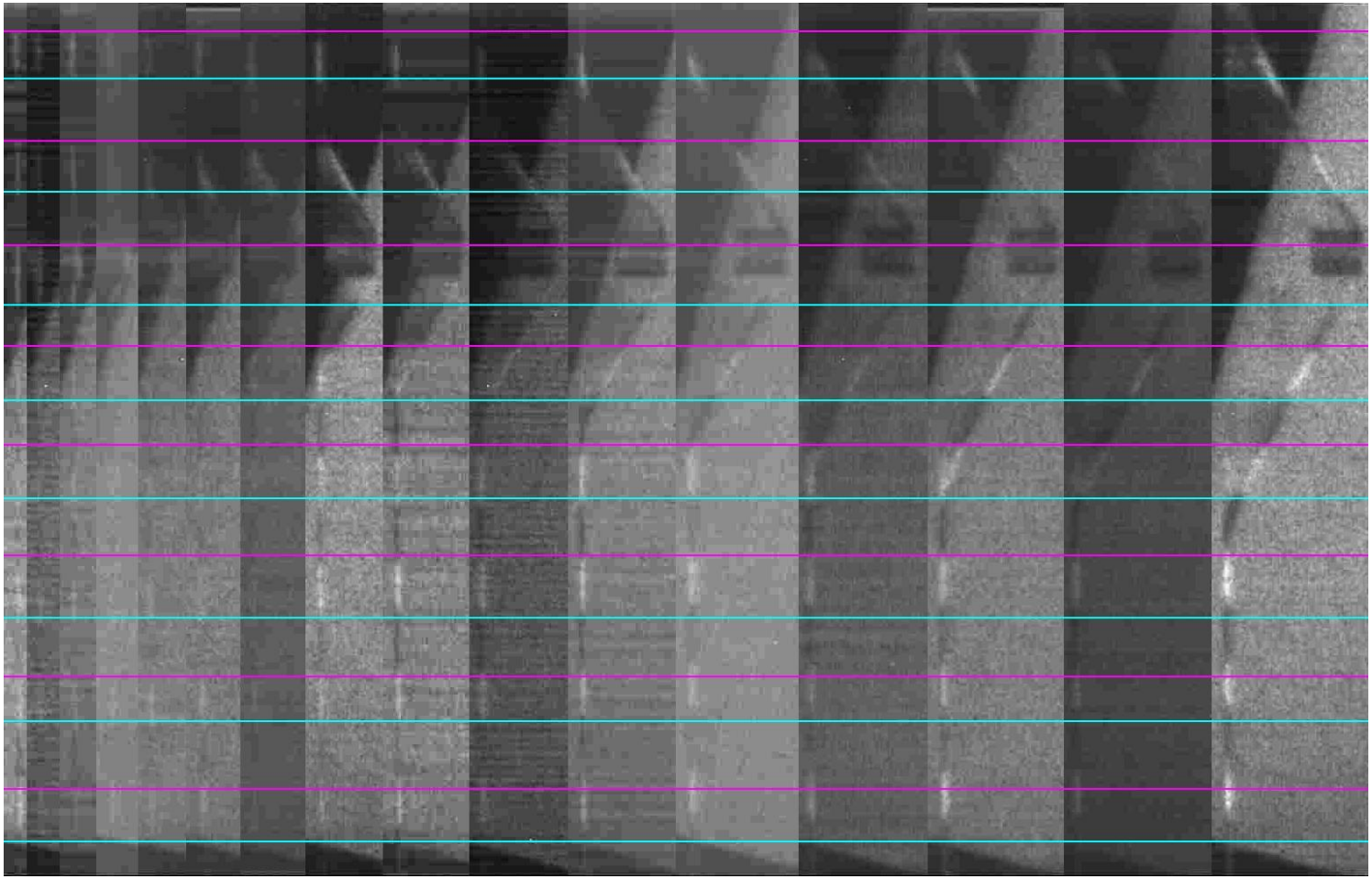
No failure

Yarn 18 – PBO – 610m/s
4 us per frame



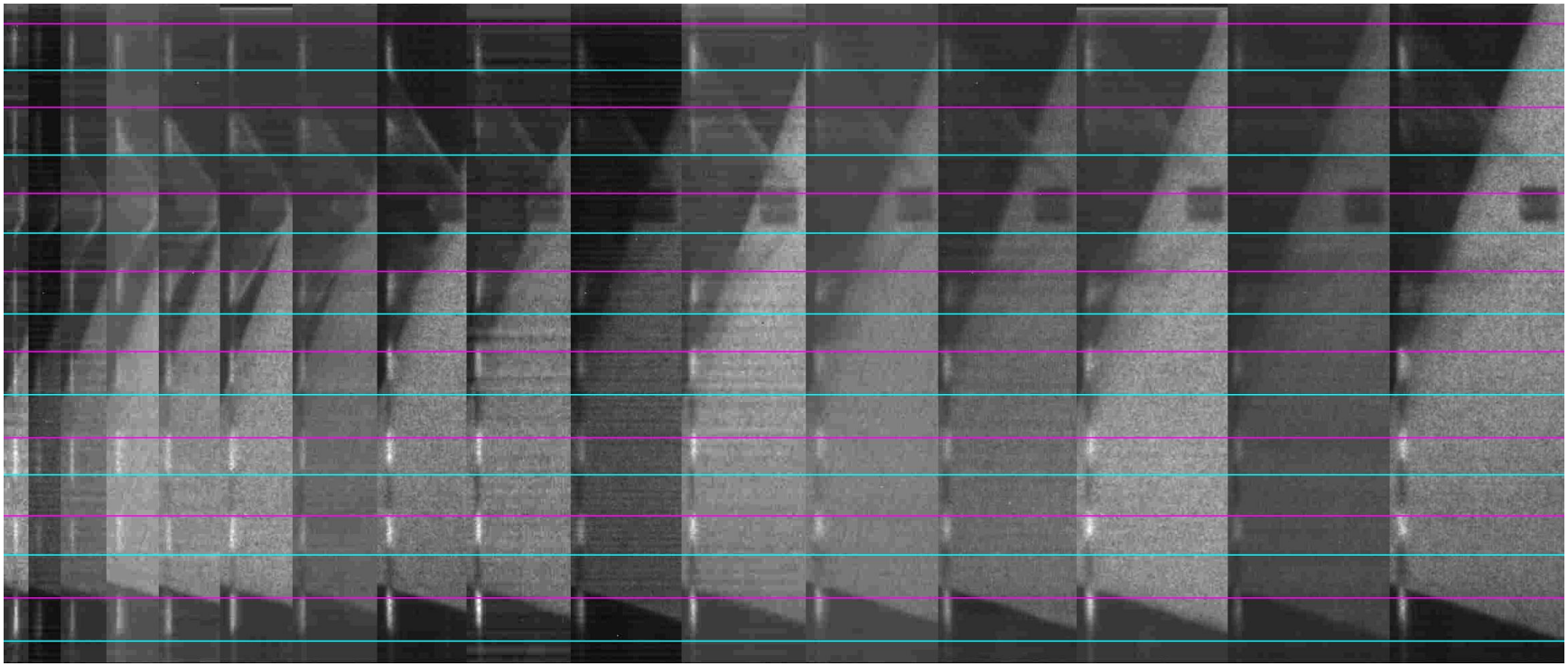
Immediate failure

Yarn 23 – 5705 – 476m/s
4 us per frame



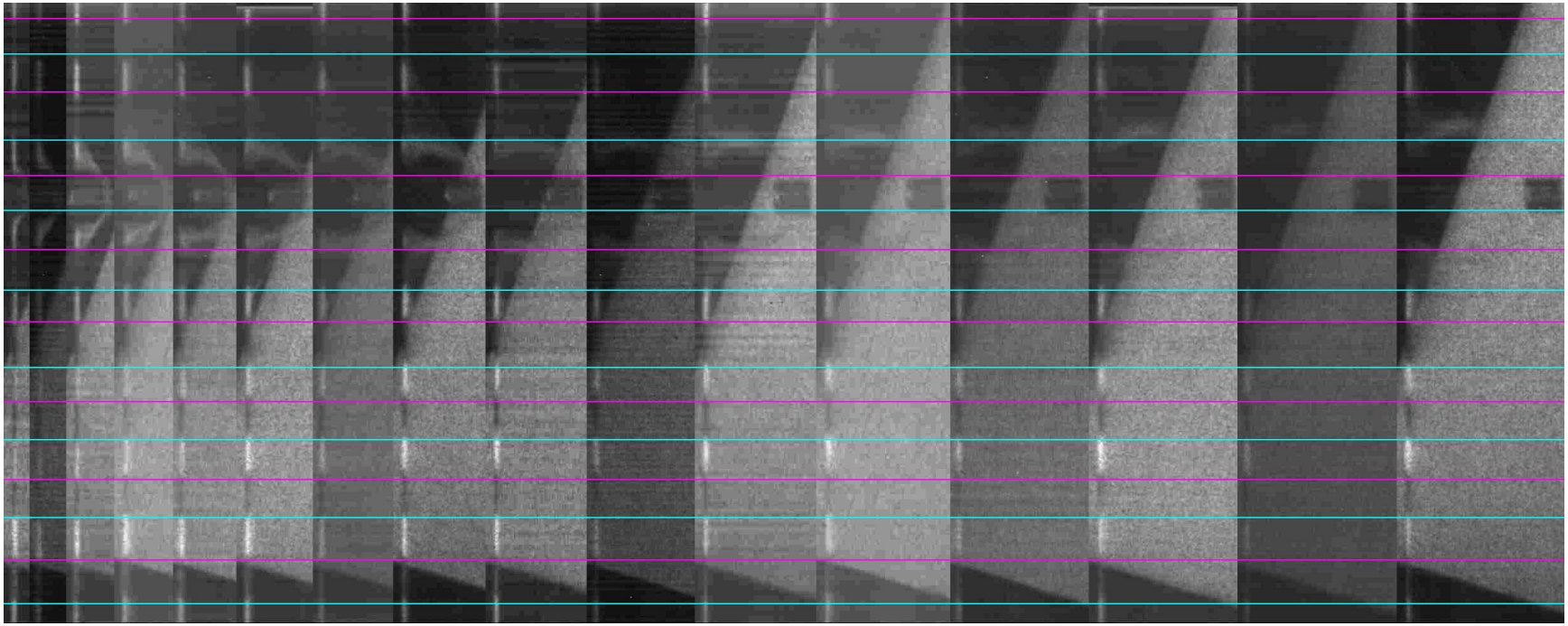
No failure

Yarn 30 – 5705 – 621m/s
4 us per frame



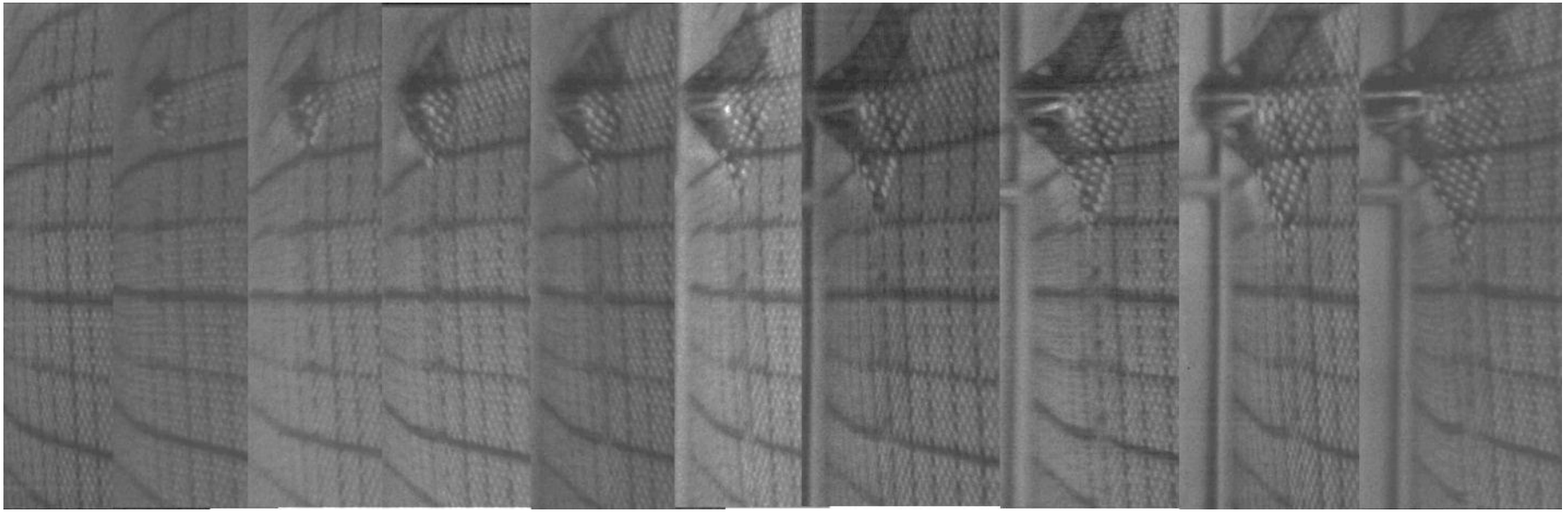
No failure

Yarn 29 – 5705 – 634m/s
4 us per frame



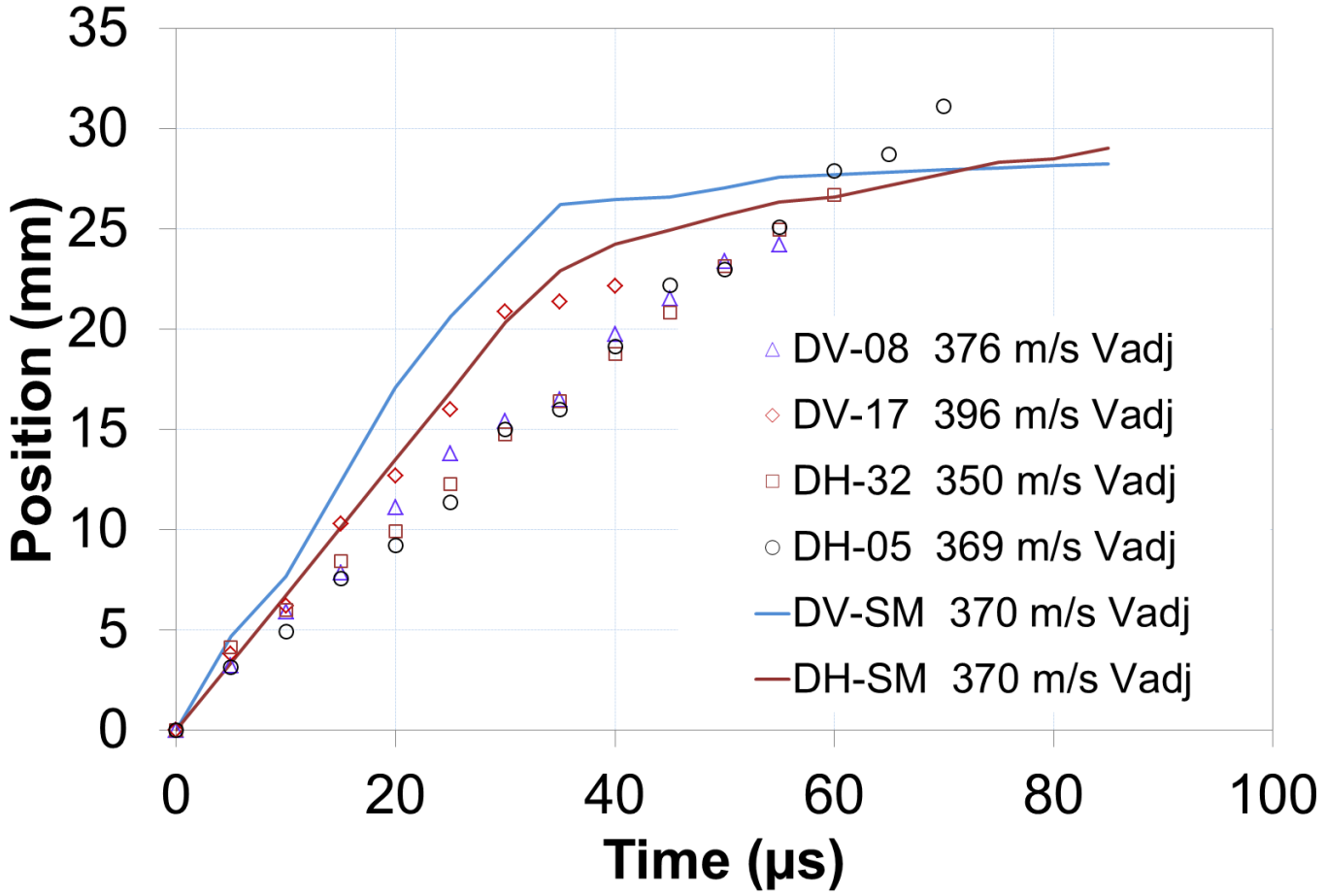
Immediate failure

Single Layer Validation



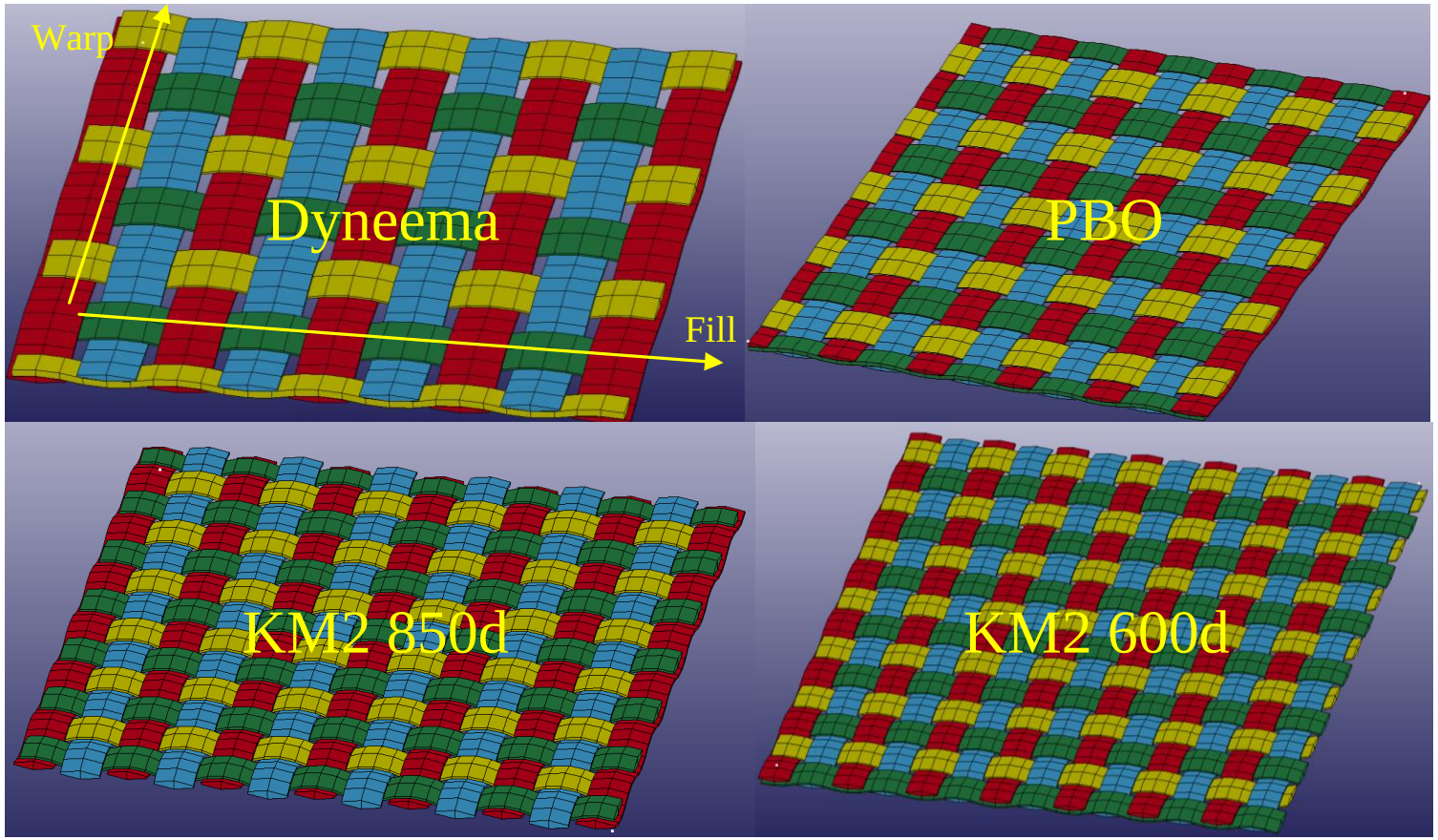
Single layer of Dyneema impacted by a .30 cal FSP at 348 m/s.
The square grid drawn on the fabric has a size of 1 cm × 1 cm.
The rightmost image shows the pyramid 45 μs after impact.

Dyneema SK-65: Single Layer Validation



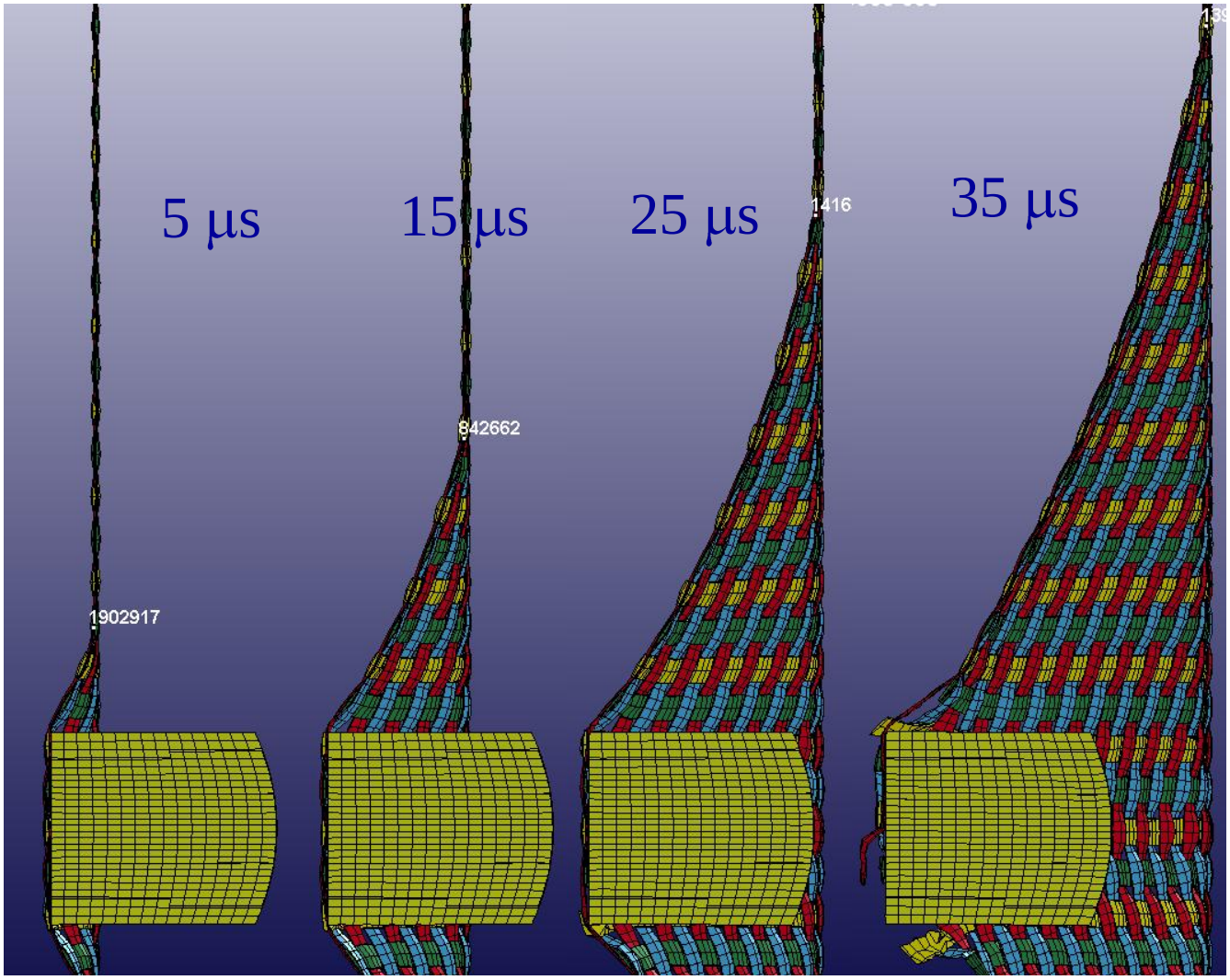
DV: Warp Direction, DH: Fill Direction

Single Layer

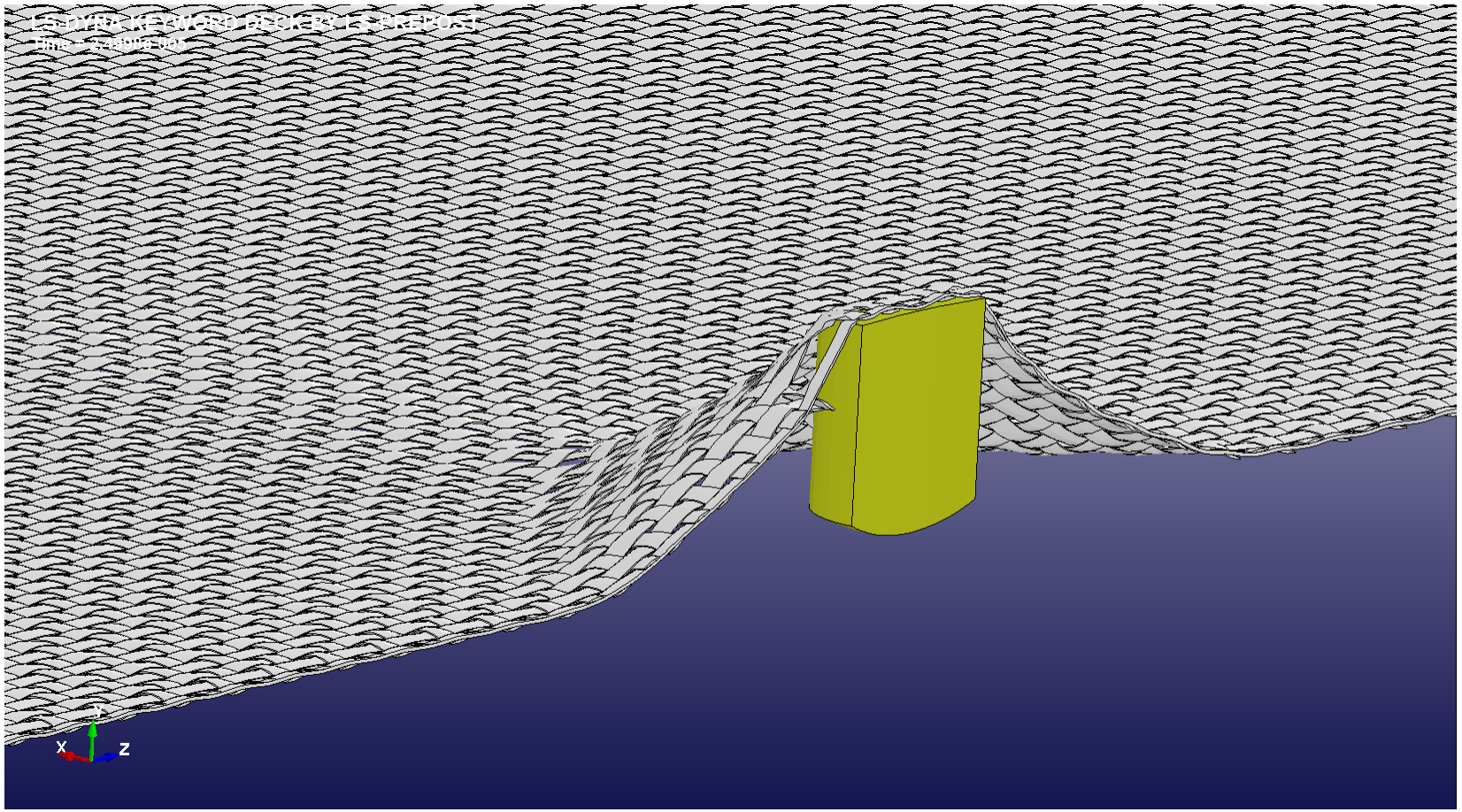


Squares (1 cm × 1 cm)

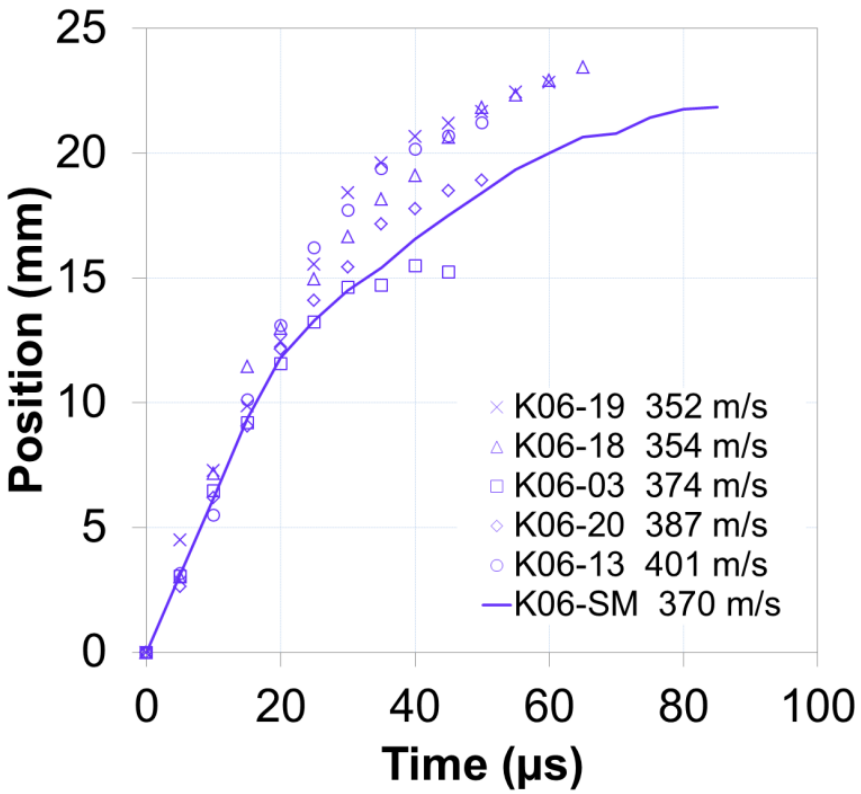
Single Layer Transverse Wave



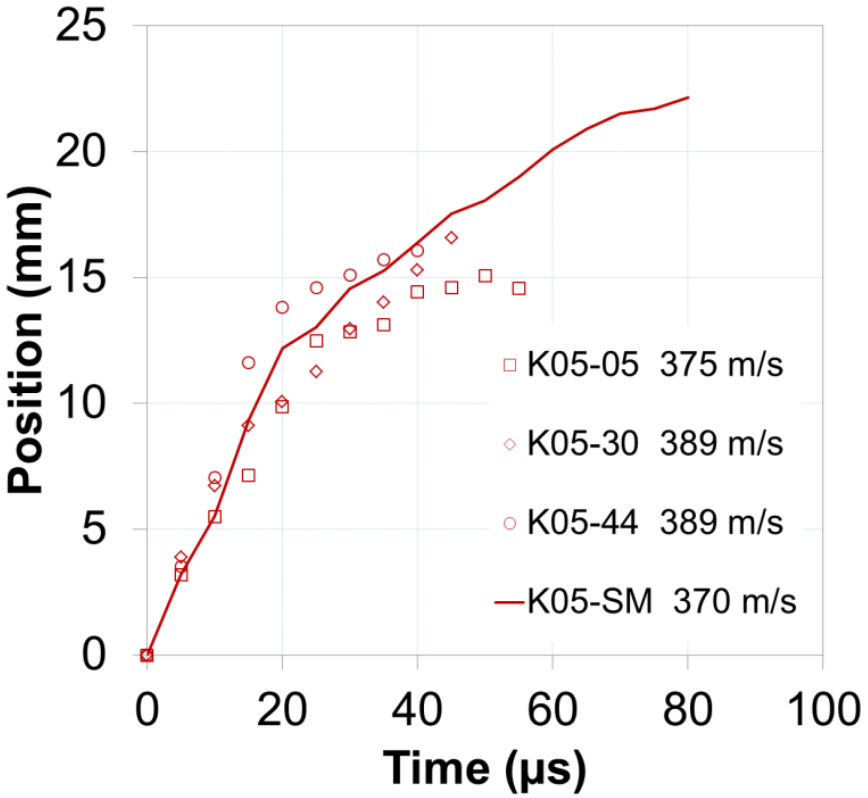
Dyneema Single Layer



Kevlar KM2: Single Layer Validation

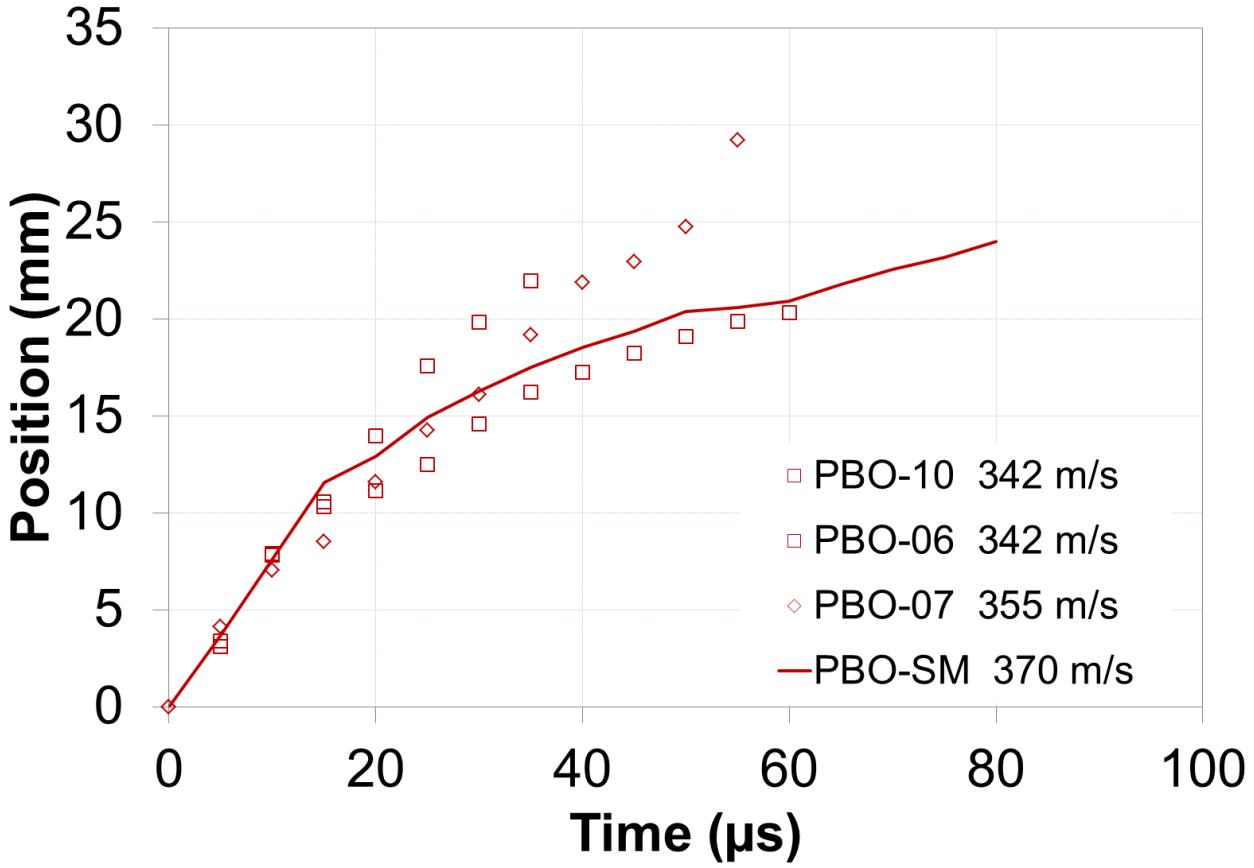


KM2 600d

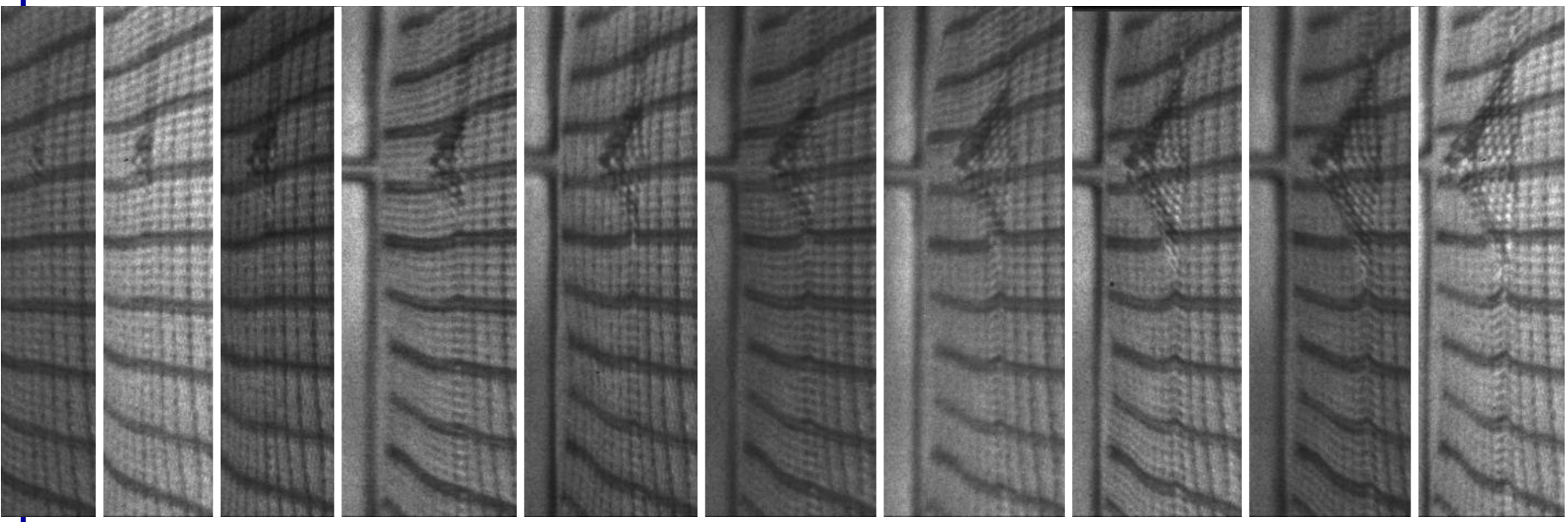


KM2 850d

PBO 500 denier, Single Layer Validation



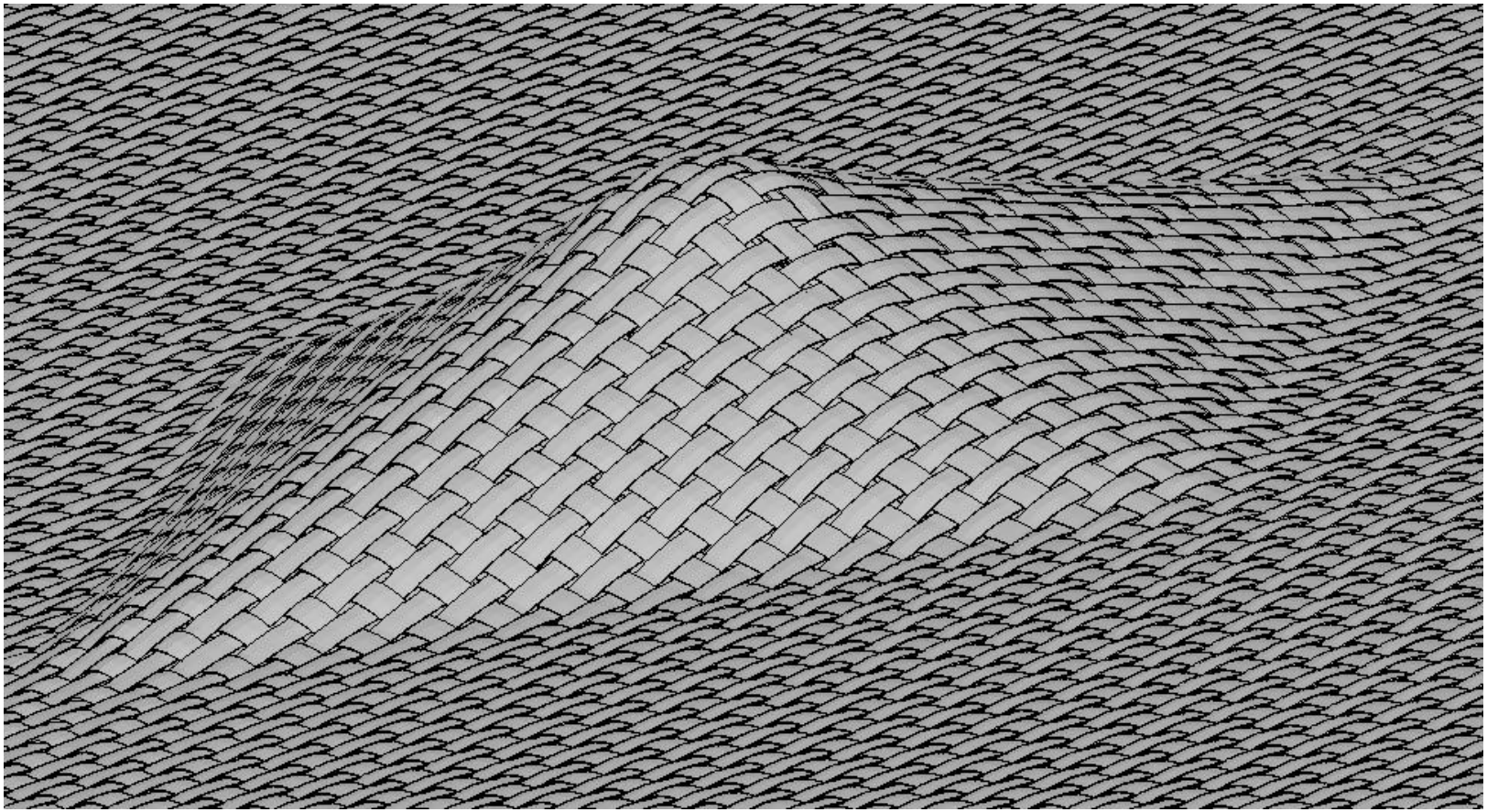
Multi-layer



5 μs intervals

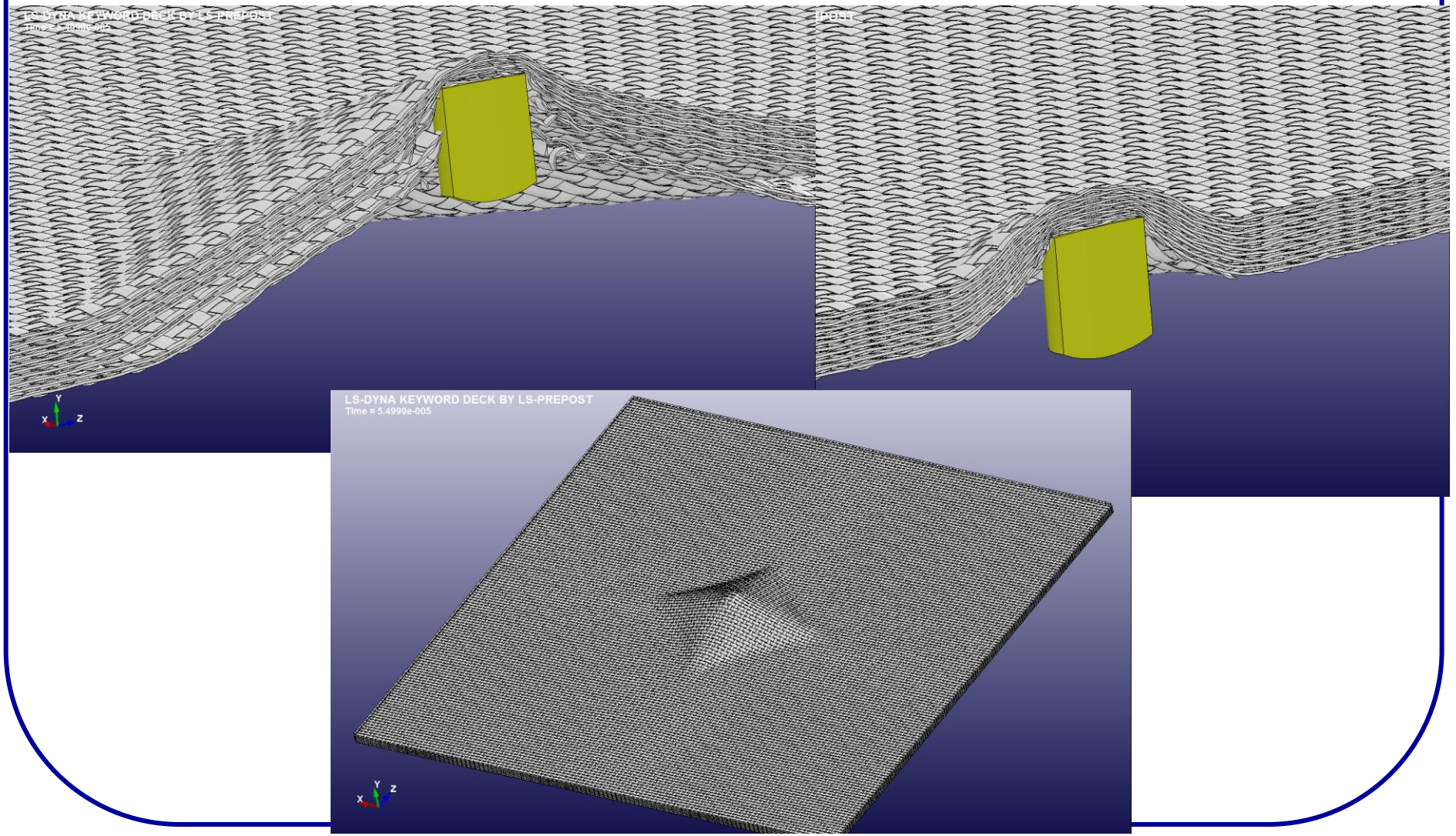
0.22 cal FSP vs. 10 layers of Dyneema at 309 m/s.

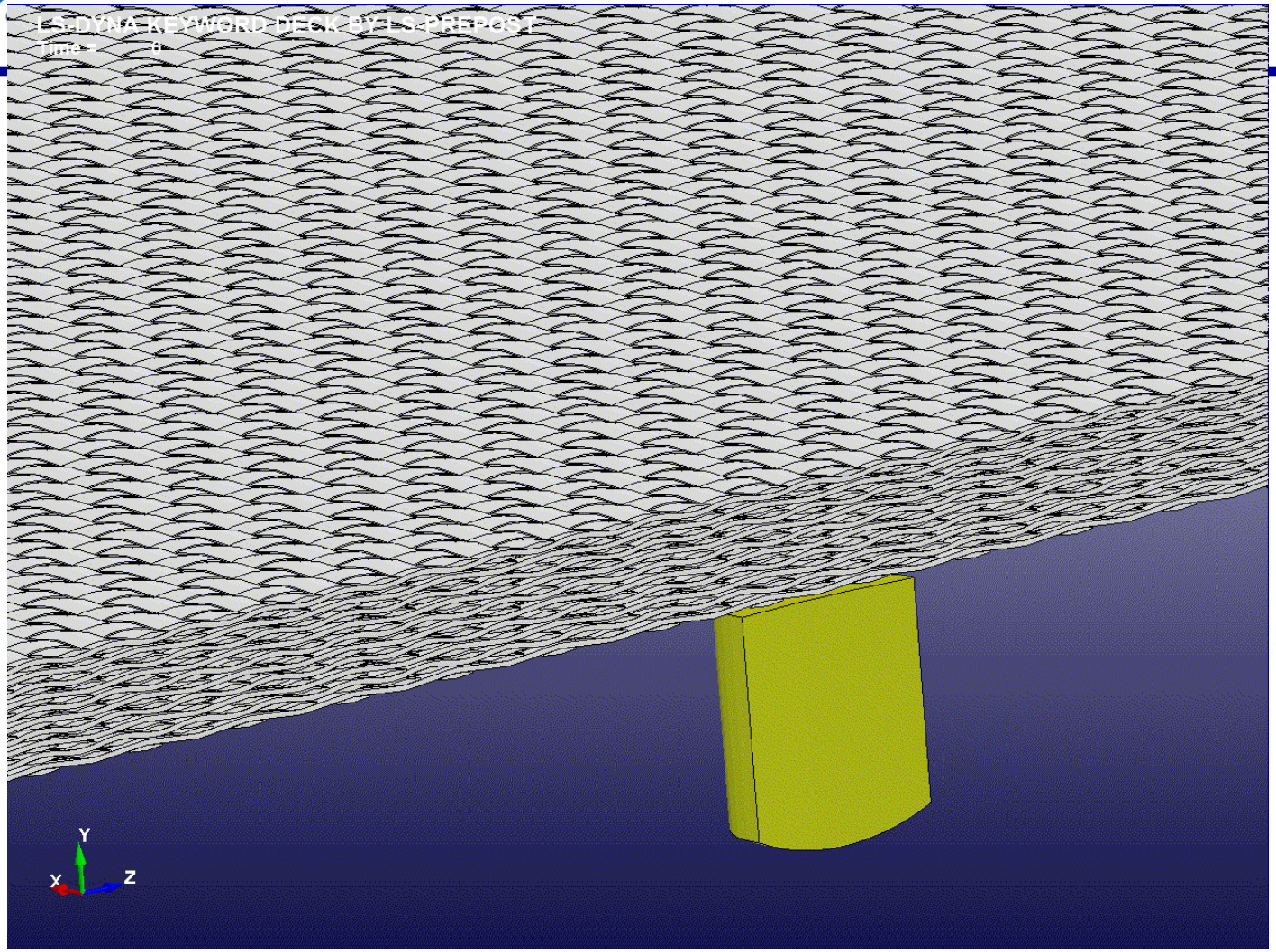
Impact on 10 Layers of Dyneema



35 μs

Dyneema 10 Layers



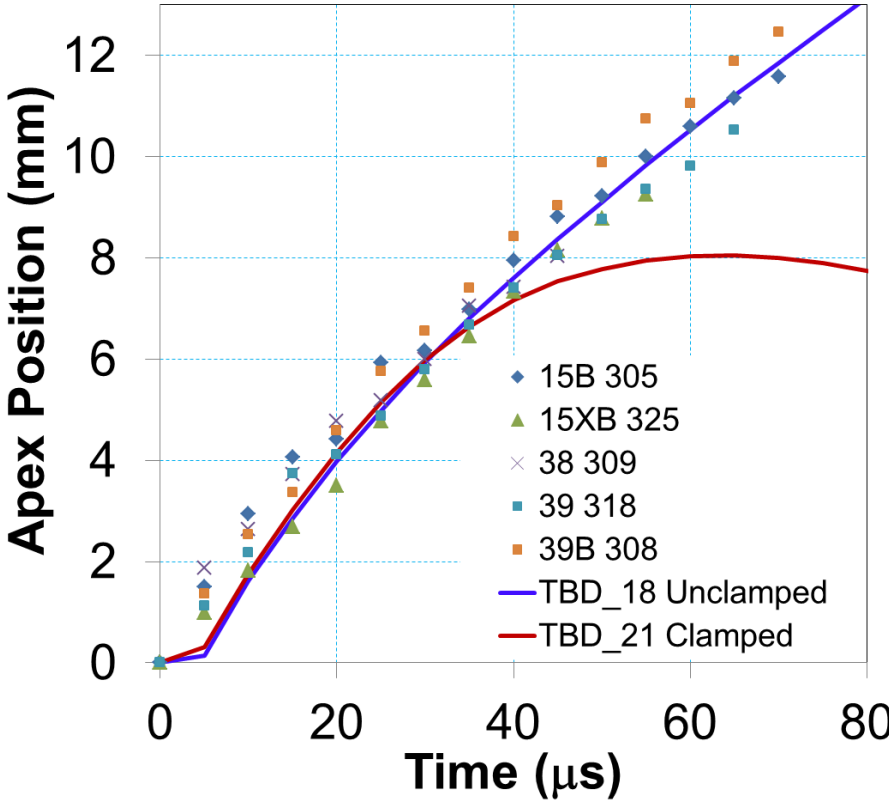

LS-DYNA KEYWORD DECK BY LS-PREPOST
Time = 0
Y
X
Z

Movies

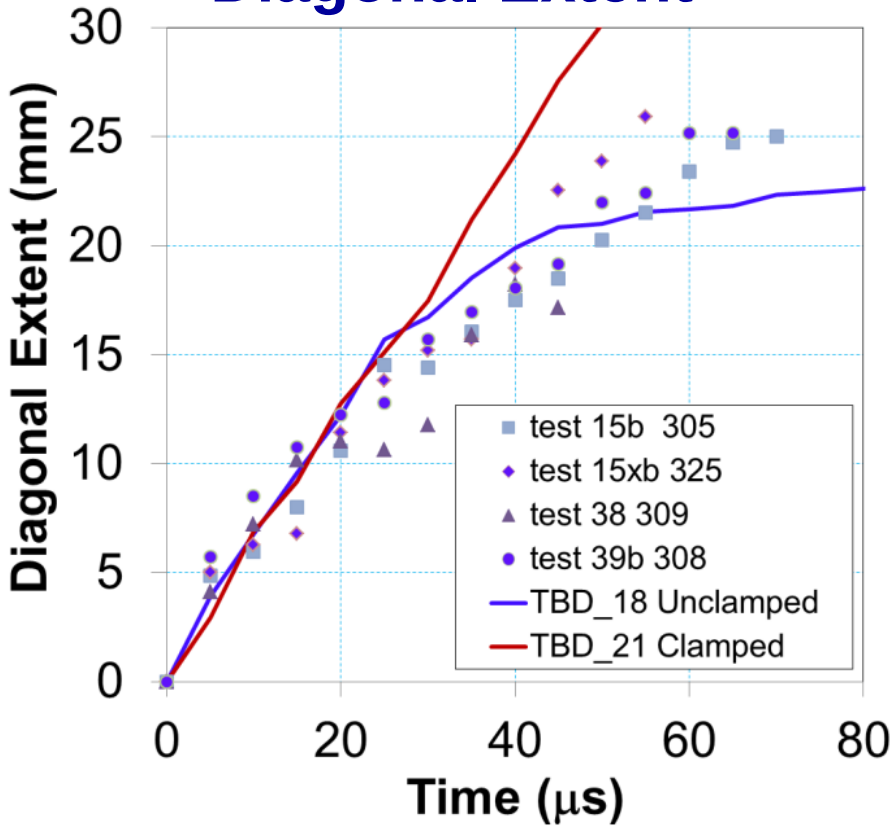
- 10 layer Dyneema and KM2 on Imacon
- 10 layer Dyneema and KM2 on Phantom
- 39 layer PBO on Imacon and Phantom

Dyneema SK-65, Multilayer Validation

Apex Position

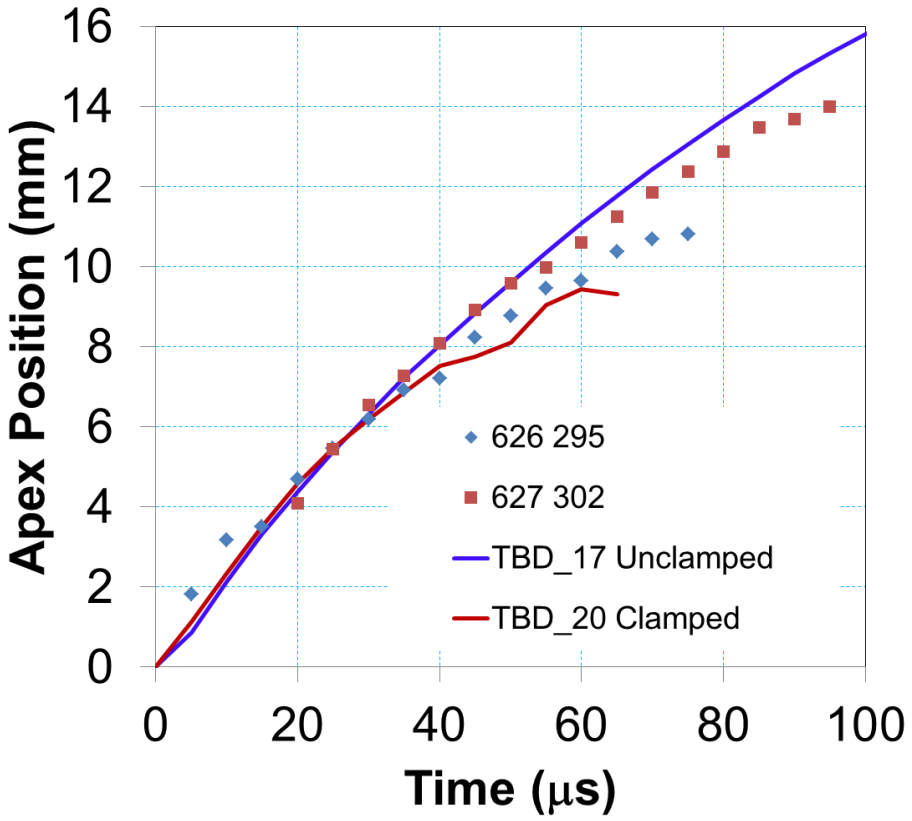


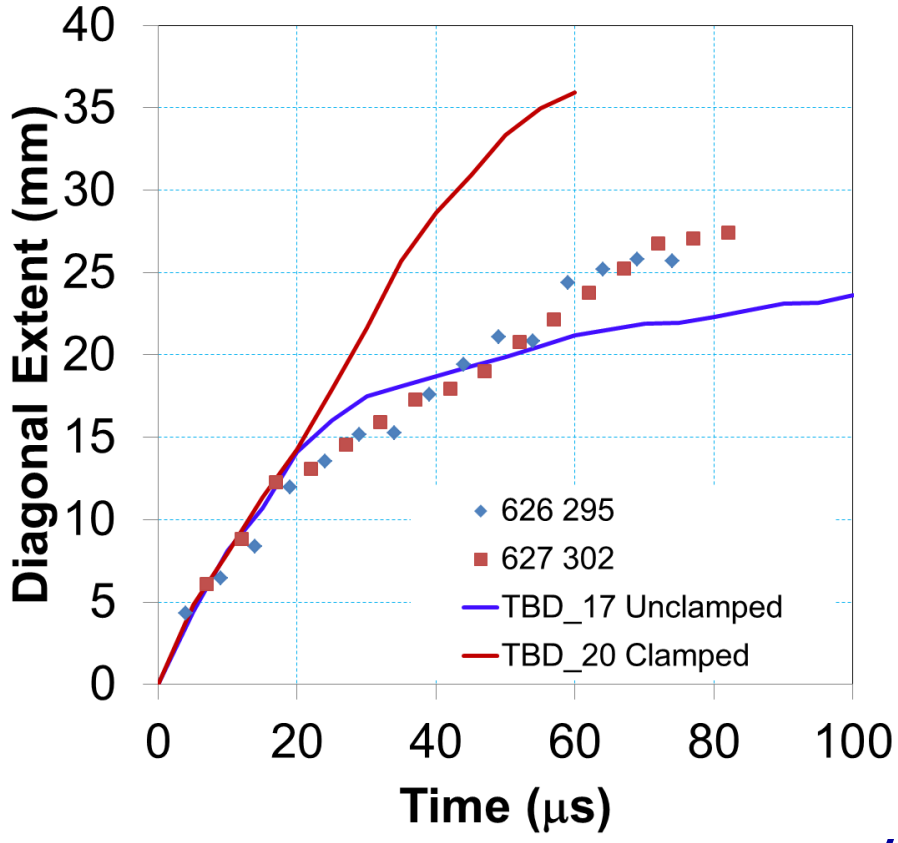
Diagonal Extent



10 layers

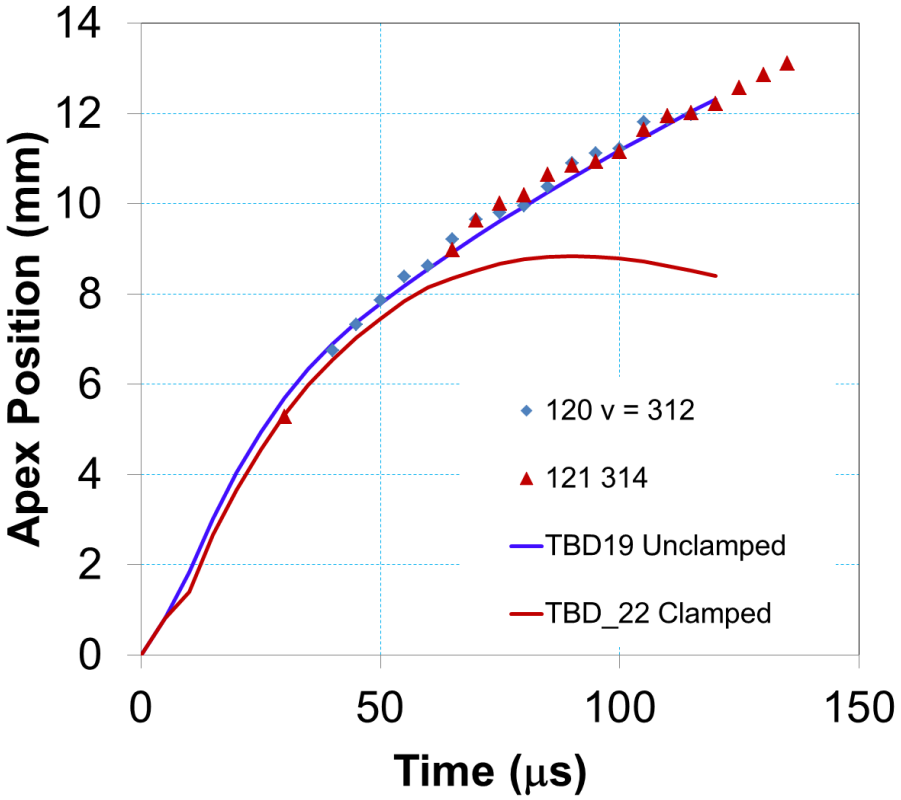
PBO 500d, Multilayer Validation

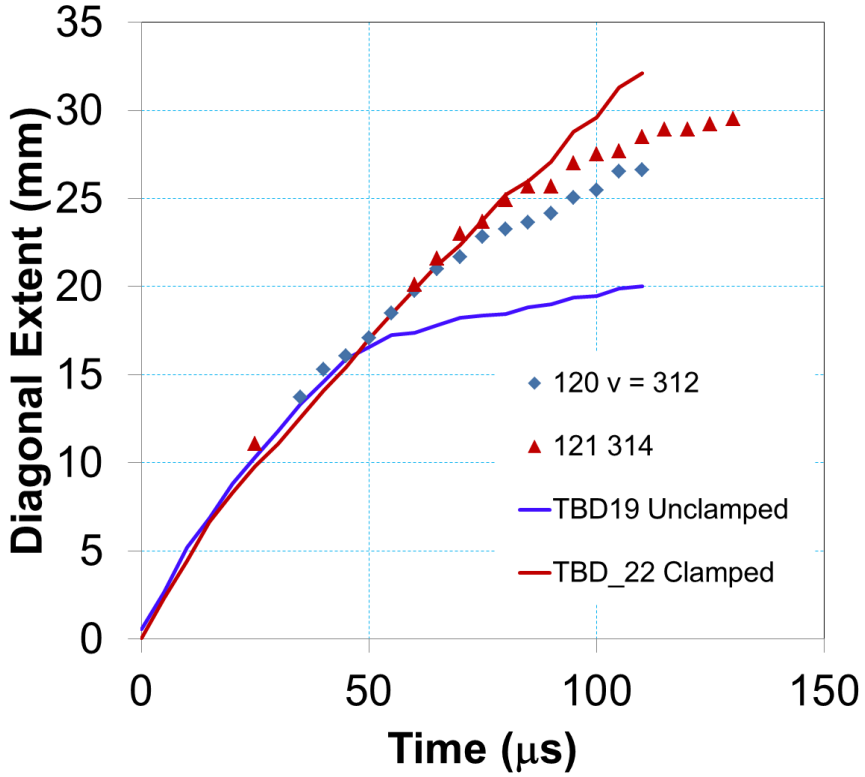




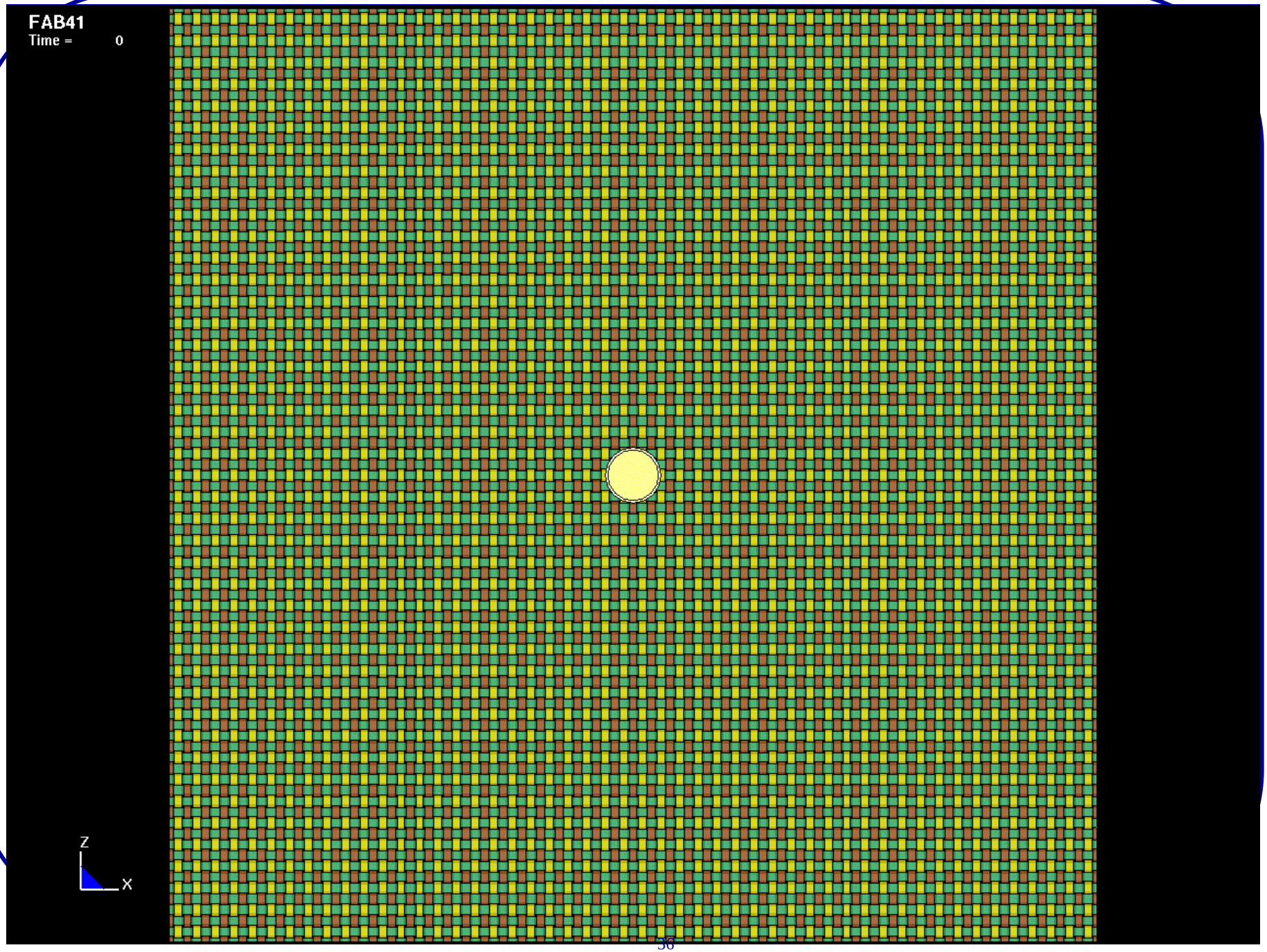
10 layers

KM2 850d, Multilayer Validation





10 layers

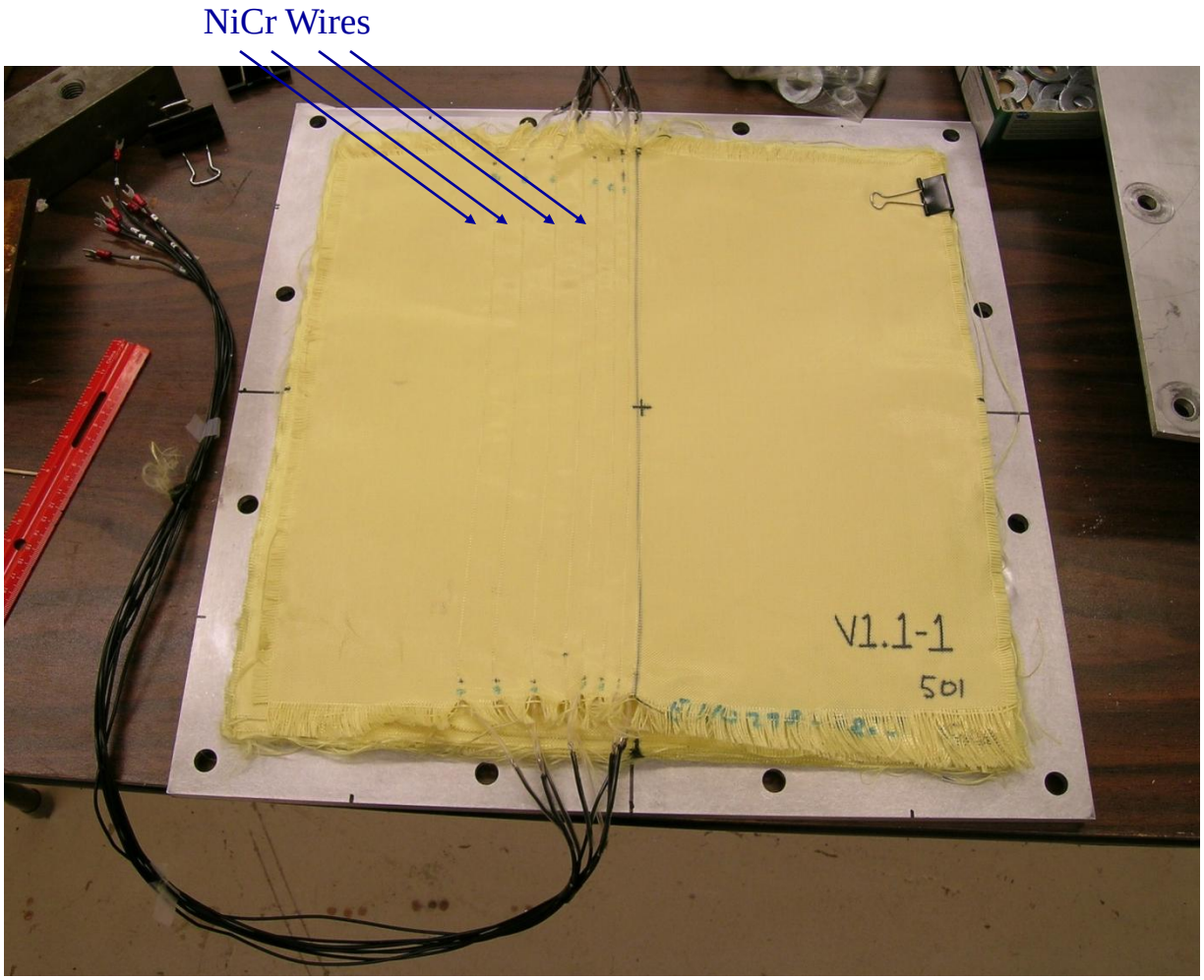

FAB41
Time = 0
Z
X

Ballistic Limits

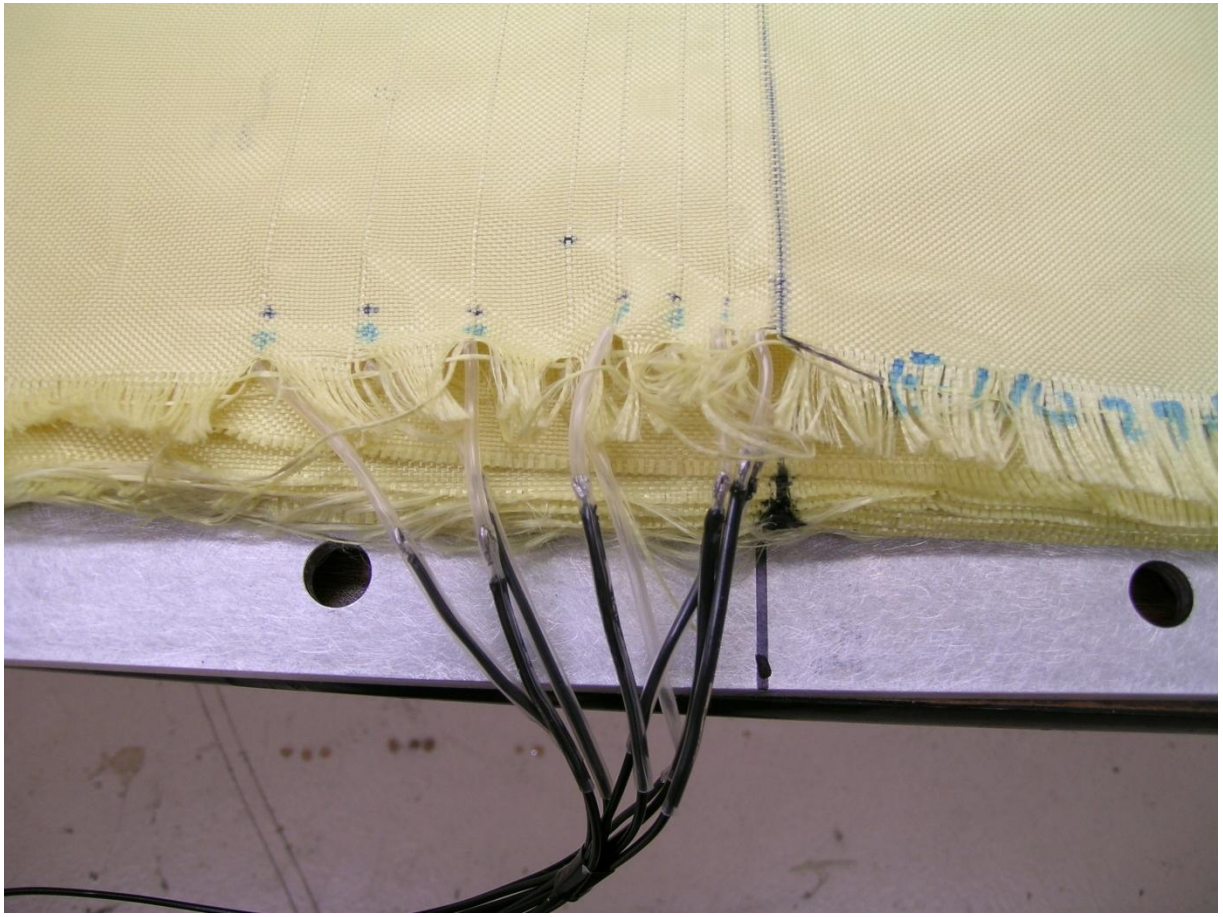
Material	FSP Projectile	Denier	Layers	Areal Density (kg/m^2)	4-shot Exp. V50/Spread (m/s)	DYNA V50 (m/s)
KM2	.30 cal	850	9	2.27	370/64	325
Dyneema	.22 cal	792	10	1.26	354/23	375
PBO	.22 cal	500	10	1.13	360/56	300

Nickel-Chromium wire technique

Test set-up: fabric with NiCr Wire



Detail of NiCr wires connections



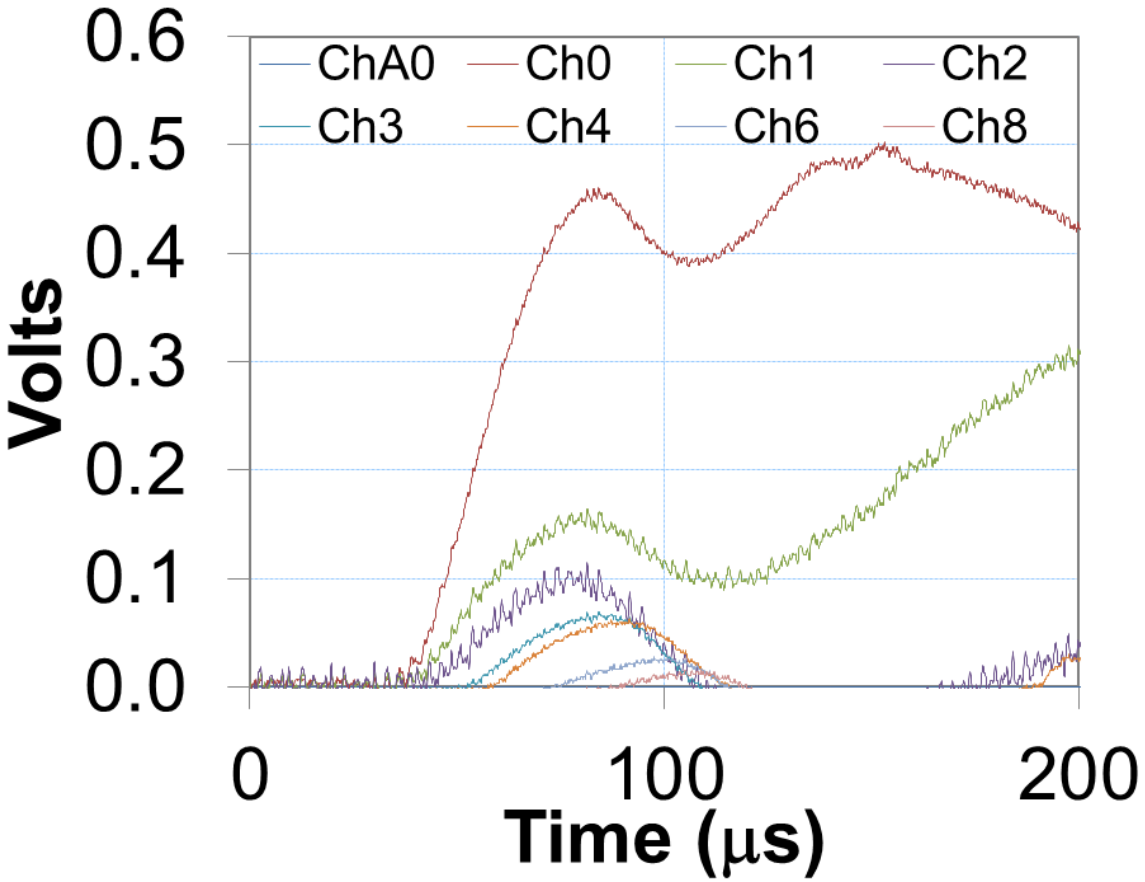
#37
VI-SK65-3
NiCr 1,12

Diagnostics - NiCr wire Acquisition System

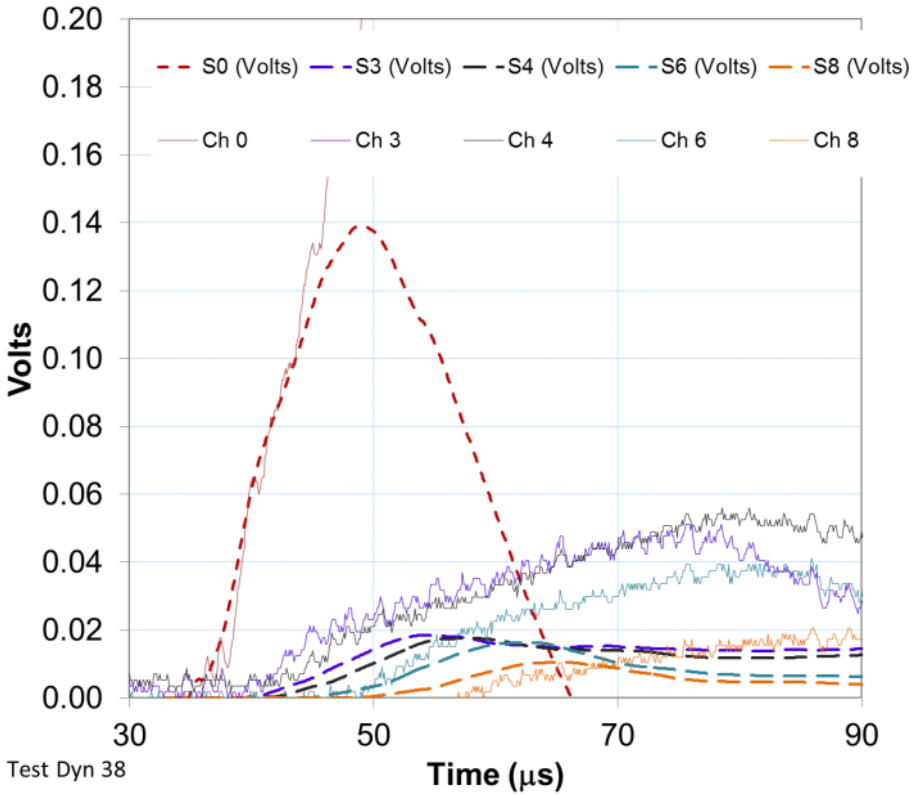
- The NiCr wires constitute one of the arms of a Wheatstone bridge (120 Ohm). The other three arms are inside the amplifiers.
- NiCr wires were calibrated in the initial phase of the project. Each NiCr wire is shunted with a 5kΩ calibration resistance to find and fine tune its calibration constant.
- The data acquisition system has a maximum of 8 channels operating at 10 MHz.

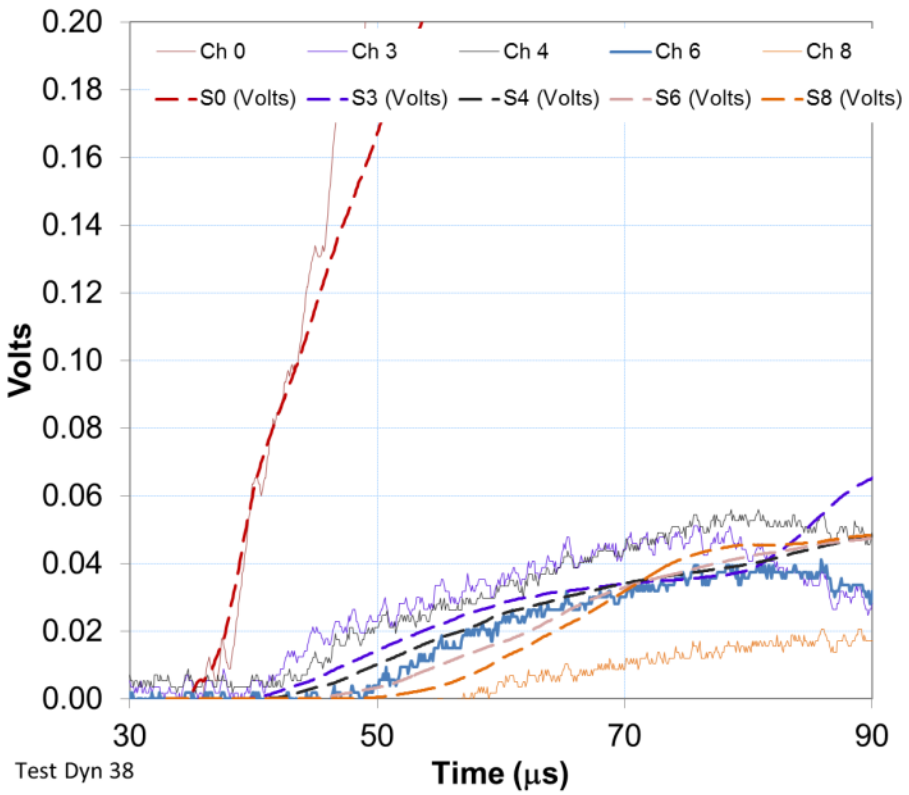
Typical Signal on KM2

- The signal is very rich
  - Longitudinal wave
  - Transverse wave
  - Failure of layer
  - Initial strain



NiCr Validation – Dyneema, 10 layers

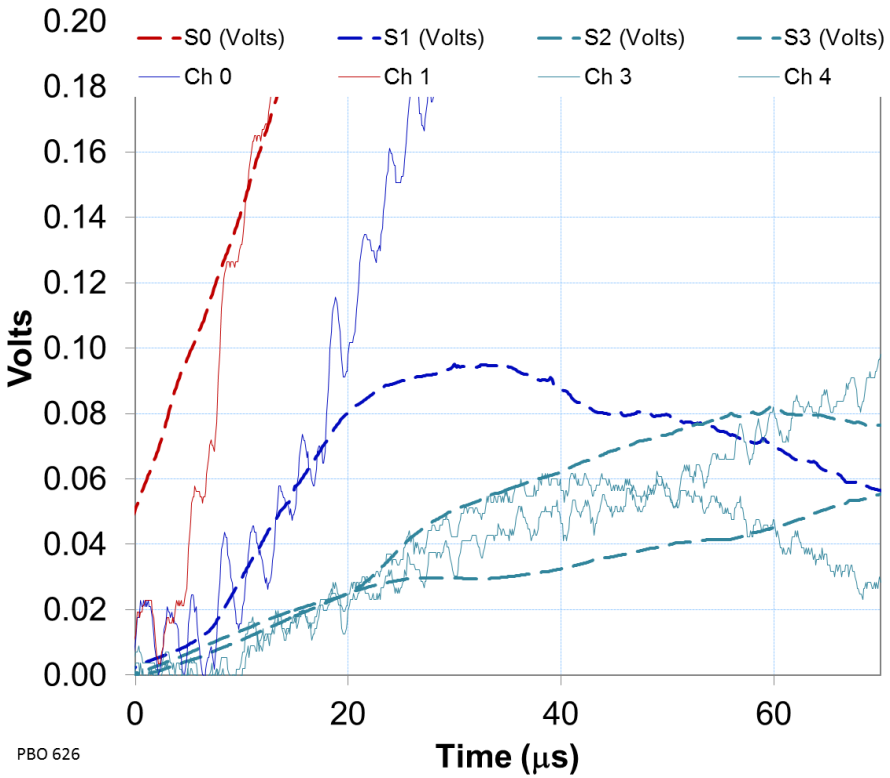


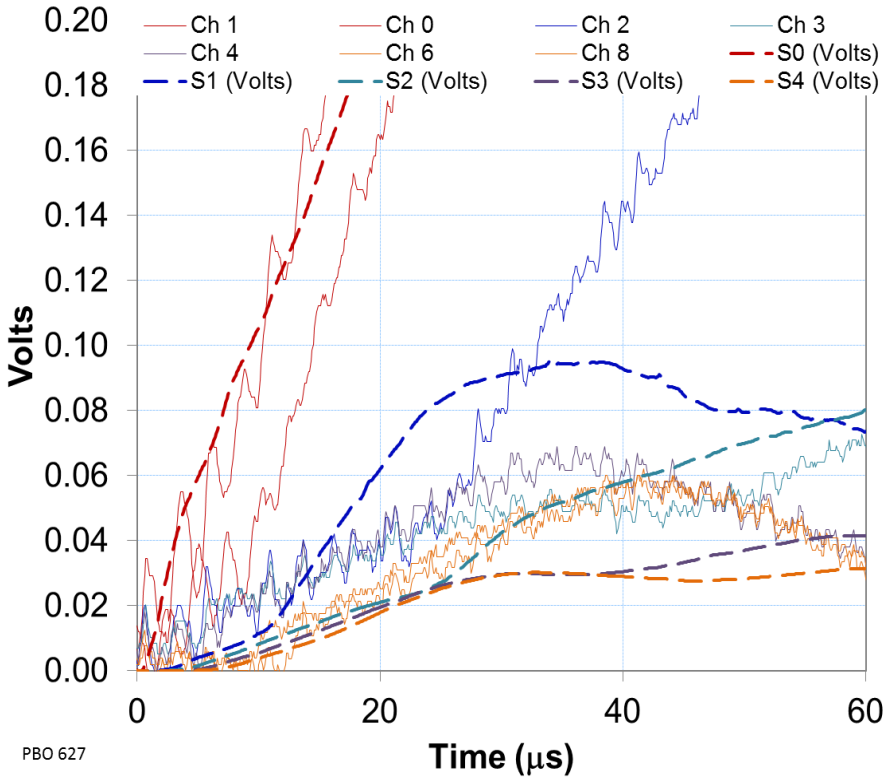


Unclamped in simulations **Clamped**

The dashed lines are the simulations, the thin lines are the waves recorded on the tests

NiCr Validation – PBO, 10 layers

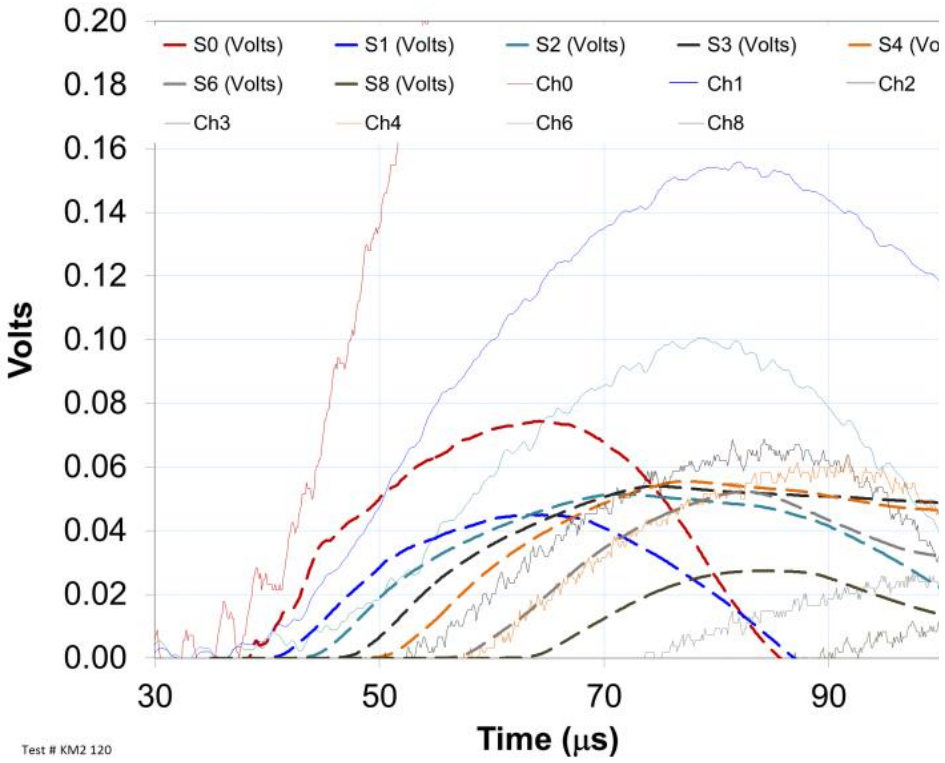


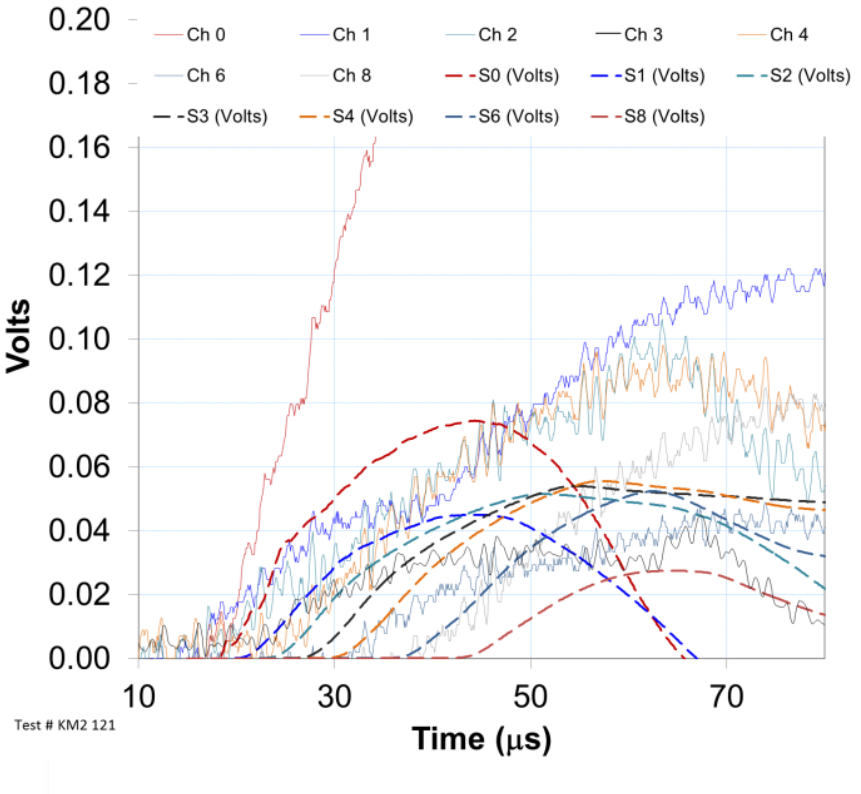


Unclamped in simulations **Clamped**

The dashed lines are the simulations, the thin lines are the waves recorded on the tests

NiCr Validation – KM2 850d, 10 layers





Unclamped in simulations **Clamped**

The dashed lines are the simulations, the thin lines are the waves recorded on the tests

Conclusions

- Use of multiple diagnostic techniques during a test increases confidence on the interpretation of the results.
- Numerical validation was performed in various ways, providing confidence on the model:
  - Single yarn impact.
  - Single layer impact.
  - Multi-layer tests.
  - Ballistic limit comparison.
  - NiCr wire waves comparison.
- Is this model perfect? NO
  - Compression of yarn in longitudinal direction has same modulus and strength.

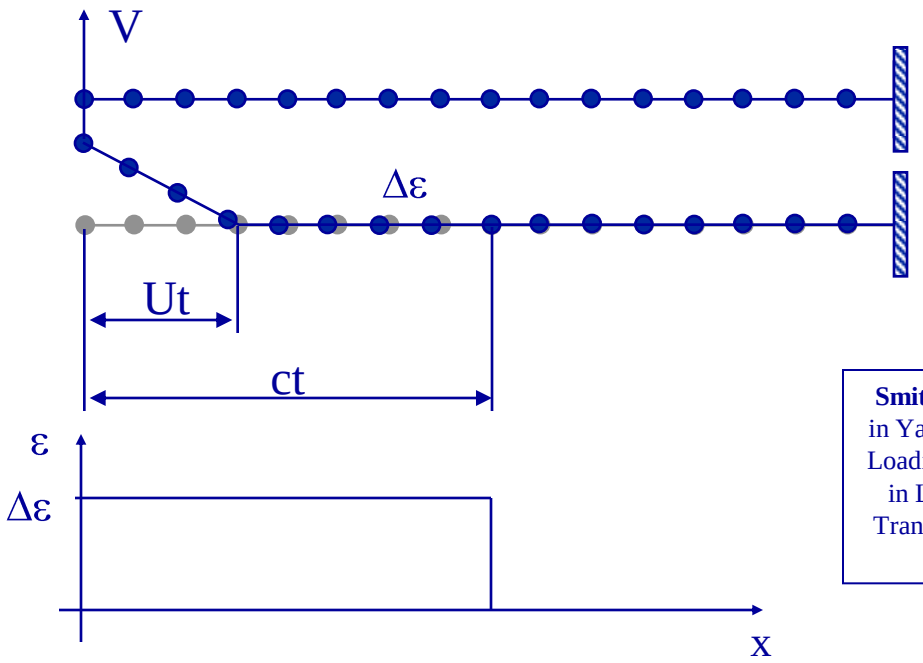
Acknowledgments

- To James Walker for his insights in the physics of the problem.
- To Harm Van der Werff from DSM for pointing out the discrepancy between theoretical and experimental critical velocities on impact on yarns.
- The authors wish to acknowledge funding for this effort provided by the Office of Naval Research through a subcontract from Johns Hopkins University Applied Physics Laboratory.
- In particular the authors wish to thank Lee Mastroianni (ONR), Jim MacKiewicz (Navy Health Research Center), and Andrew Merkle (JHU-APL).

Backup Slides

Wave propagation in yarns (Smith, 1958)

- Yarn wave propagation well known:
  - Longitudinal wave travels at speed of sound c
  - Transverse wave travels slow at a speed U
- Wave reflects on boundary and impact point increasing by $\Delta\varepsilon$ at each reflection until yarn breaks.



Smith, Stress-Strain Relationships in Yarns Subjected to Rapid Impact Loading: Part V: Wave Propagation in Long Textile Yarns Impacted Transversely, Textile Res. Journal, 1958; 28; 288

Wave propagation in yarns (Smith, 1958)

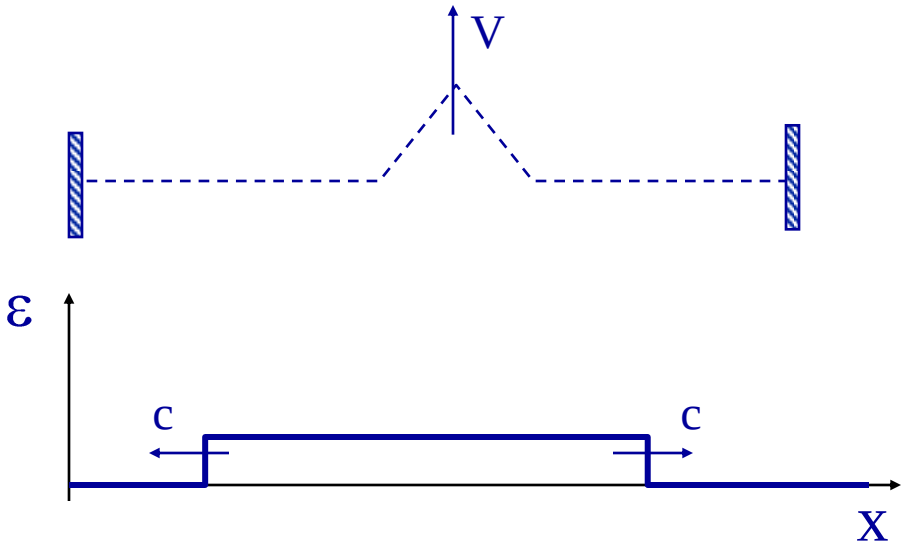
- Given impact velocity and sound speed in the yarn it is straightforward to determine strain and transverse wave velocity:

$$V = c\sqrt{\varepsilon\left(2\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon\right)}$$

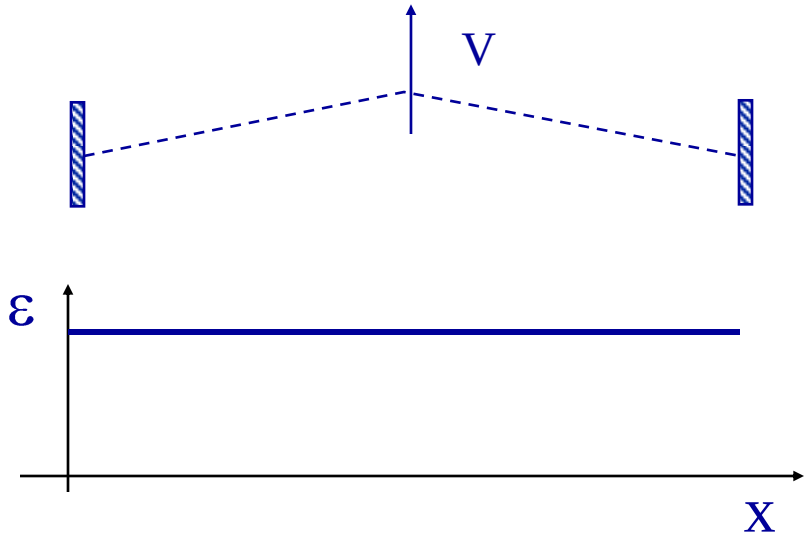
$$U = c\left(\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon\right)$$

Smith, Stress-Strain Relationships in Yarns Subjected to Rapid Impact Loading: Part V: Wave Propagation in Long Textile Yarns Impacted Transversely, Textile Res. Journal, 1958; 28; 288

Local vs. global strain



Early time ($t \sim t_c$)
Local response
NiCr does not directly give the strain
Need a model to interpret V(t)



Late time ($t >> t_c$)
Global or structural response.
NiCr "directly" gives strain with $\varepsilon = k \times V$

Characteristic time: $t_c \equiv .5\ L/c$
For our tests: $t_c \sim 40\ \mu s$

"Local" strain - Model for the longitudinal wave

Given the above assumption and the fact that the voltage drop depends on the strain as:

$$V(x,t) = \frac{1}{k_w}\int_0^x \varepsilon(x,t)dx$$

Then

$$V(t) = 2\frac{\varepsilon_0 c_{fab} t}{k_w}$$

Where ε_0 is the strain that is propagating through the yarn. V is then linear with time for the first few microseconds. The *local* strain in the NiCr yarn for the first few microseconds is:

$$\varepsilon_0 = \frac{k_w V(t)}{2c_{fab} t}$$

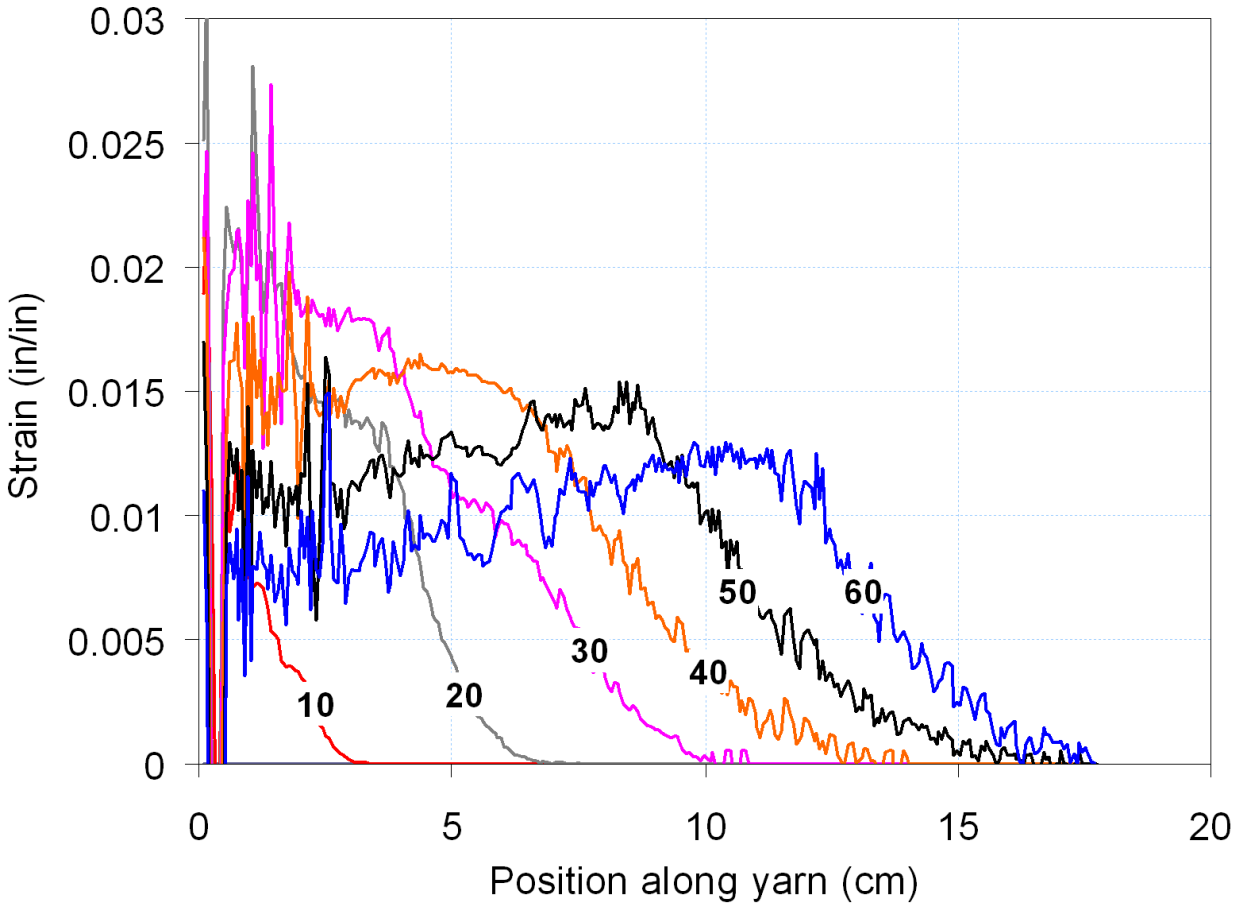
and, since V is proportional to the time (αt) for the first few microseconds:

$$\varepsilon_0 = \frac{k_w \alpha}{2c_{fab}}$$

Sources of error when evaluating strain

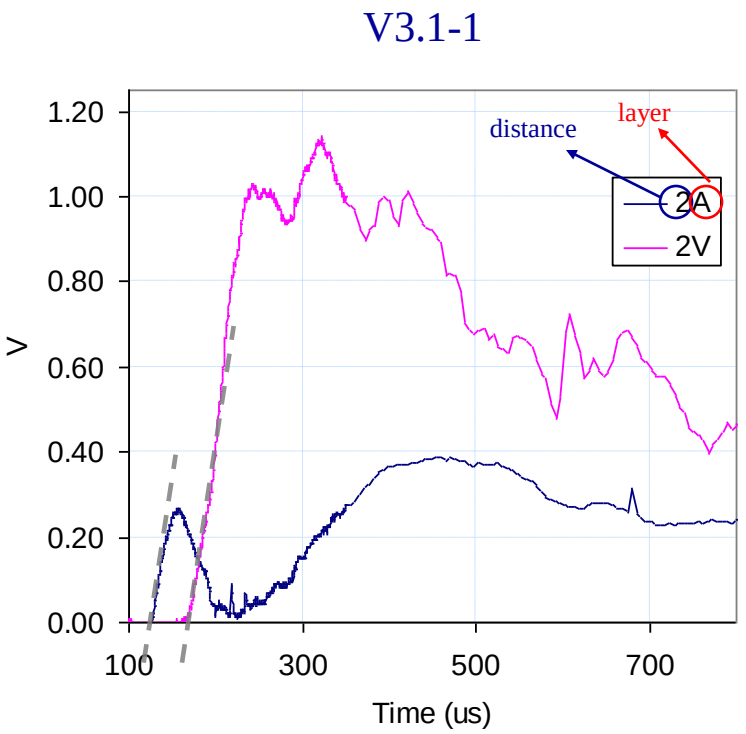
- Local strain:
  - The propagation of the longitudinal wave is in fact much more complex. At each crossover part of the wave is reflected and part transmitted.
  - The wave probably damps at some point and does not seem to be reflected at the boundary since that would mean doubling the slope of V(t), which does not happen in the experiments
- Global strain:
  - Confidence is higher when measuring global strain because the NiCr wire is used as a long strain gage.
  - Nevertheless some error is introduced by not taking into account the slippage of fabric at the boundaries.
  - Maximum slippage is around 3 inches (adding both top and bottom boundaries)
  - This increases the gage length of the wire and, systematically, gives us a strain higher than the real one (if, when converting voltage to strain we keep the gage length constant)
  - If we assume that max. slippage happens at max. strain (conservative assumption) then the max. error is ~0.5% strain (so a 20% relative error for a 2.5% strain measurement). A typical error is ~0.3% strain (12% relative error).
  - Again, the error is not random but systematically we estimate more strain than the real strain.
  - At high velocities or for the Vamac® targets this error is very small (<0.1% strain)

Strain in the Impacted Yarn (LS-DYNA)



Description of the waves seen in the NiCr wire

- The principles, main assumptions and limitations of the NiCr wire technique are discussed in a paper published in the Int. J. of Impact Engng. in 2010.
- We assume the waves are divided in four parts:
  - Initial pull: First 10 or 15 μs, which, we assume, correspond to a longitudinal wave traveling up the yarn/wire. Linear part.
  - Failure and/or transverse wave (if it happens): following 30 – 50 μs. The transverse wave shows up as a linear segment. Failure shows up as a bump
  - Mixed region: complex wave interaction, region difficult to interpret ~ 500 or 1000 μs
  - Global response: late time (quasi-steady) that can be interpreted as in a static tensile test: ~ 1000 μs or more

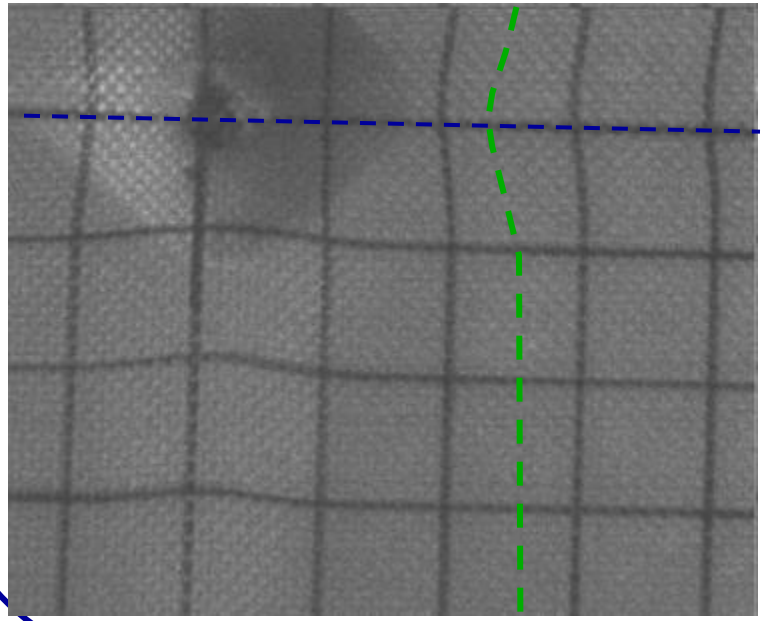


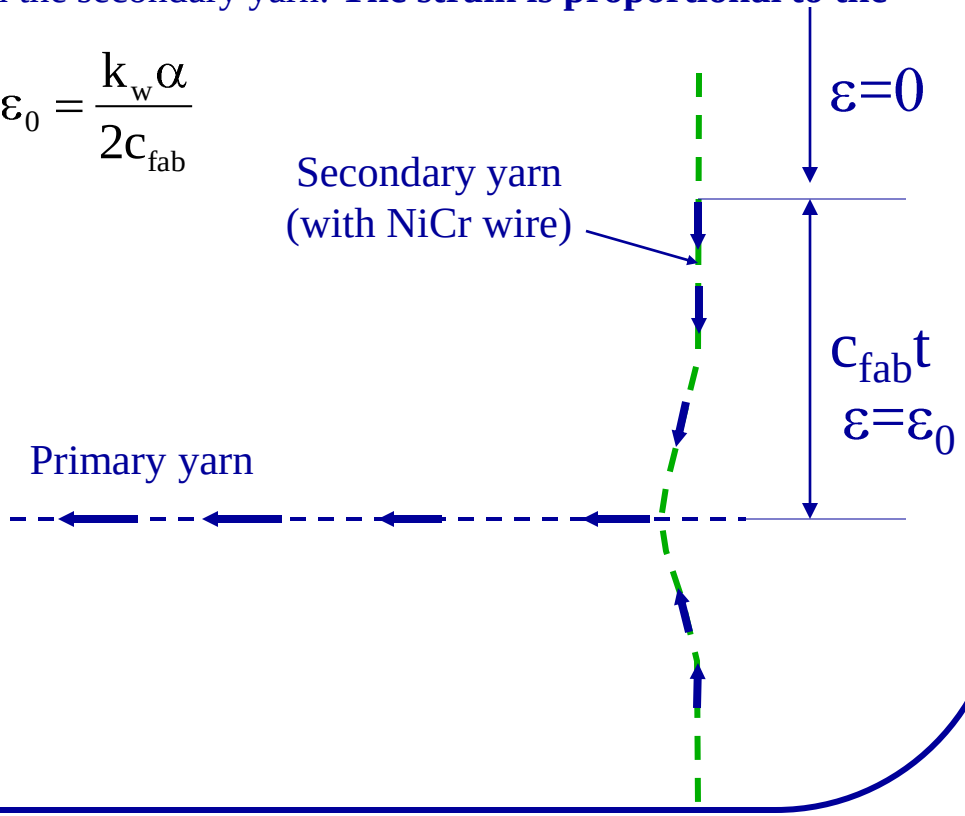
This particular test had a NiCr wire in the first and last layer. The first layer was perforated during the test. The last layer was not perforated

Model for the longitudinal wave

- Assumption: The first slope in V=V(t) is due to a longitudinal wave traveling through the secondary yarn (the one that has the NiCr wire) at a speed c_{fab}.
- This longitudinal wave gives rise to a constant strain that travels along the yarn. This assumption is only good for the first few microseconds, until failure or transverse wave arrival.
- Purpose: Allow to calculate the *local* strain in the secondary yarn. **The strain is proportional to the initial slope**.

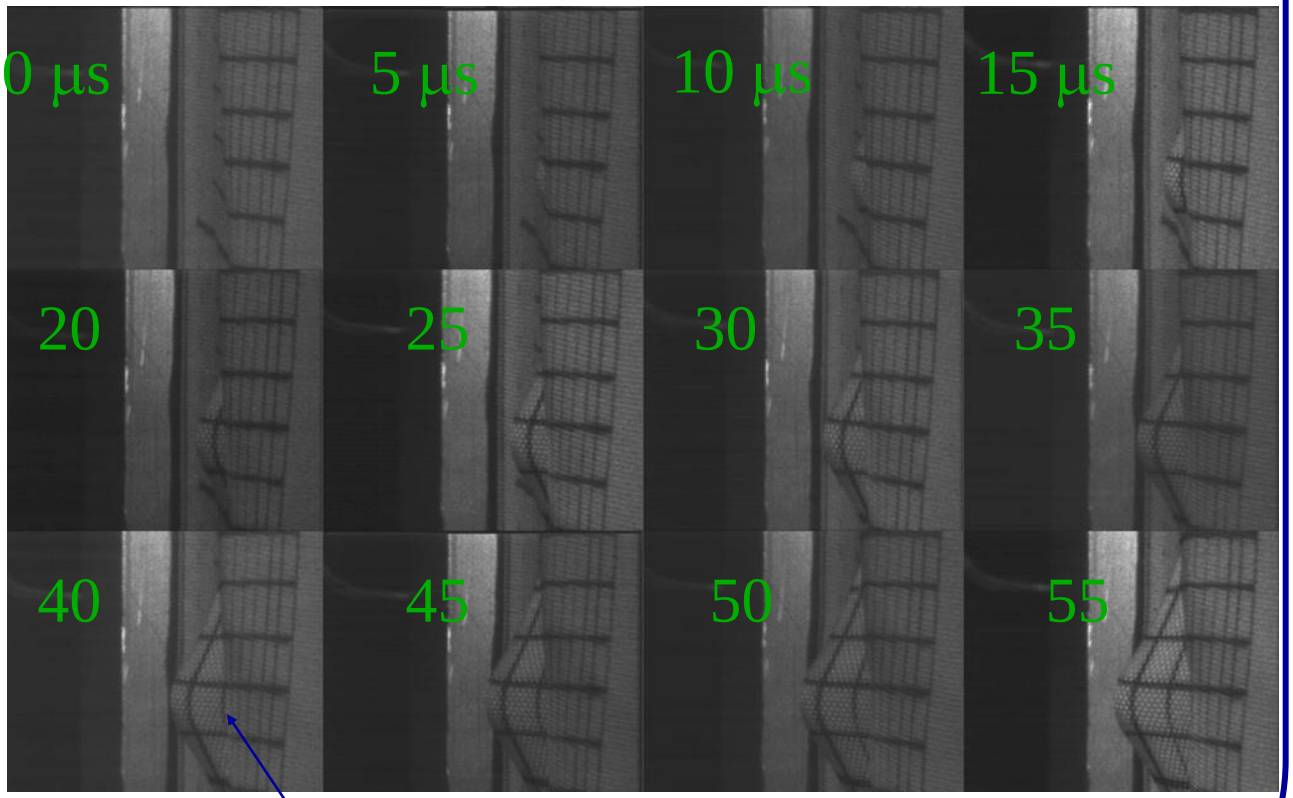
$$\varepsilon_0 = \frac{k_w \alpha}{2 c_{fab}}$$





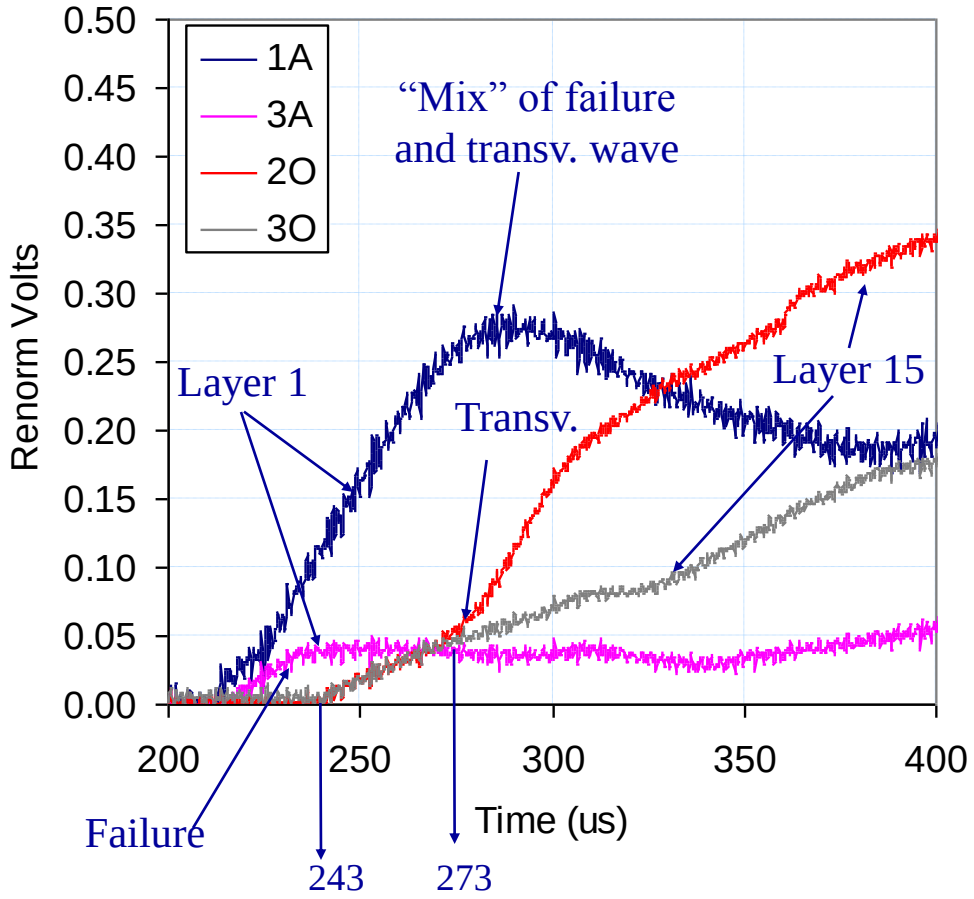
V3.1-1

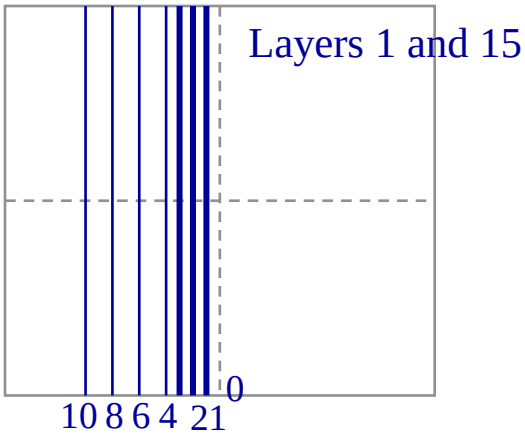
- It takes ~ 35 μs for the transverse wave to reach the NiCr wire



V1.10-2

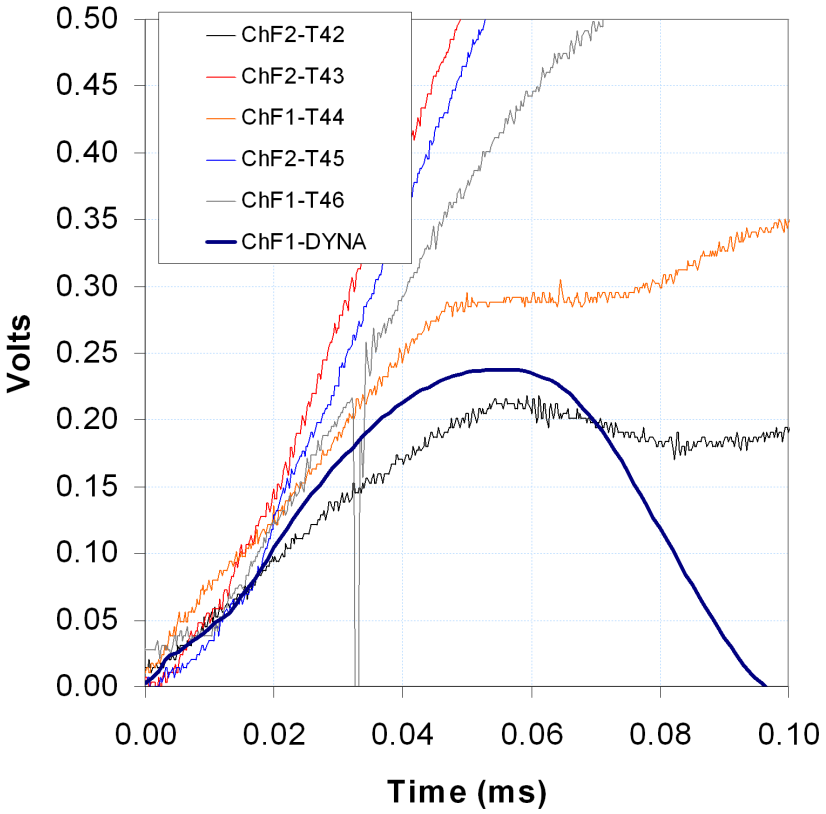
NiCr on layers 1 and 15; 2 first layers penetrated



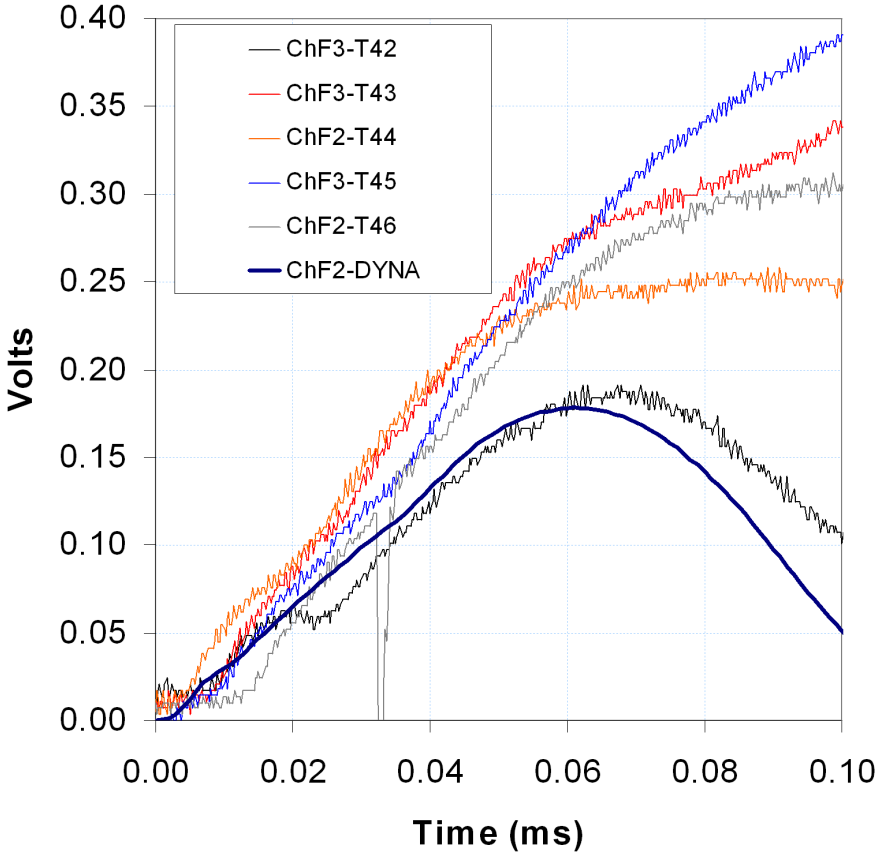


Comparison of signals from tests vs. signals from simulations

DYNA vs. NiCr wire

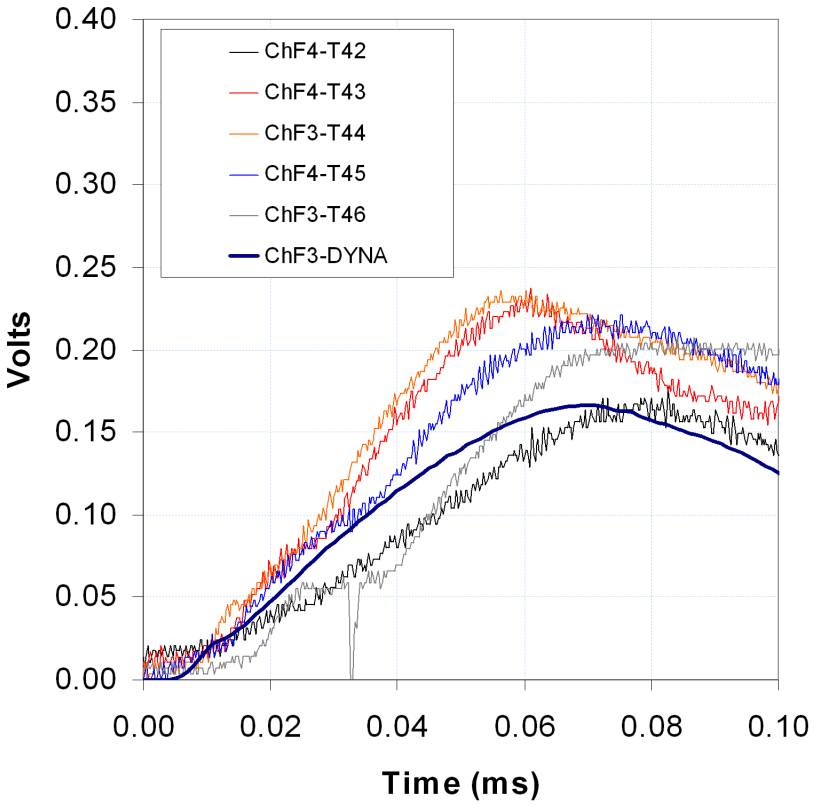


1 cm from impact point

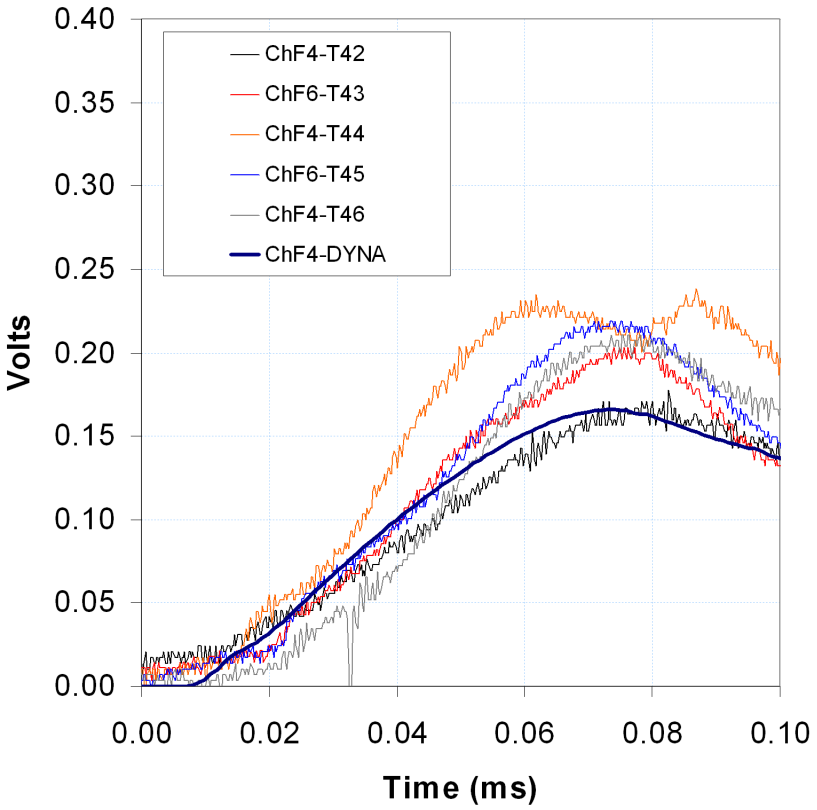


2 cm from impact point

DYNA vs. NiCr wire

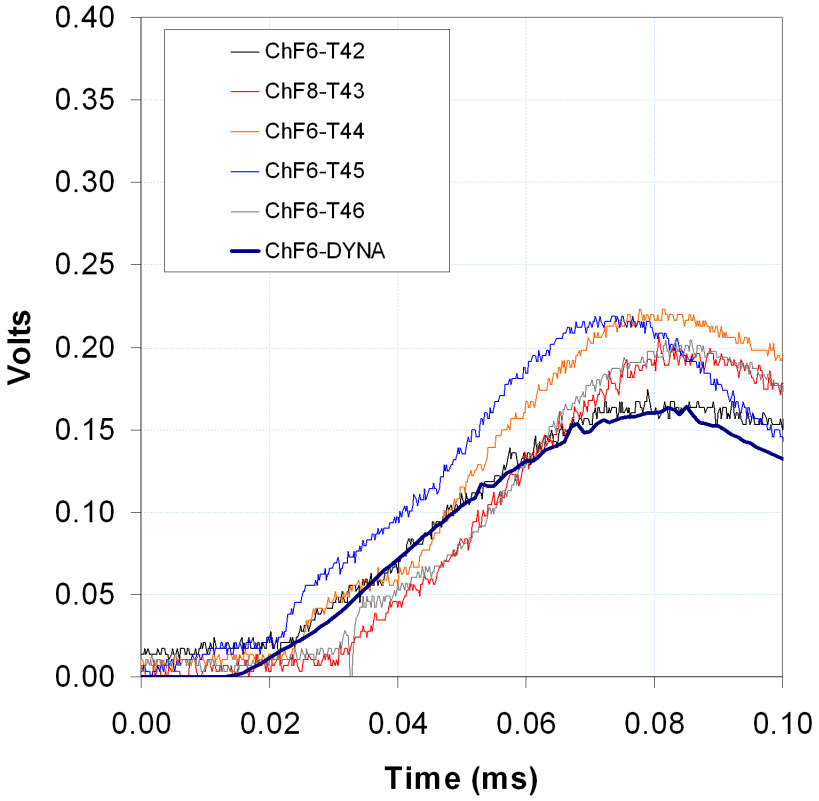


3 cm from impact point

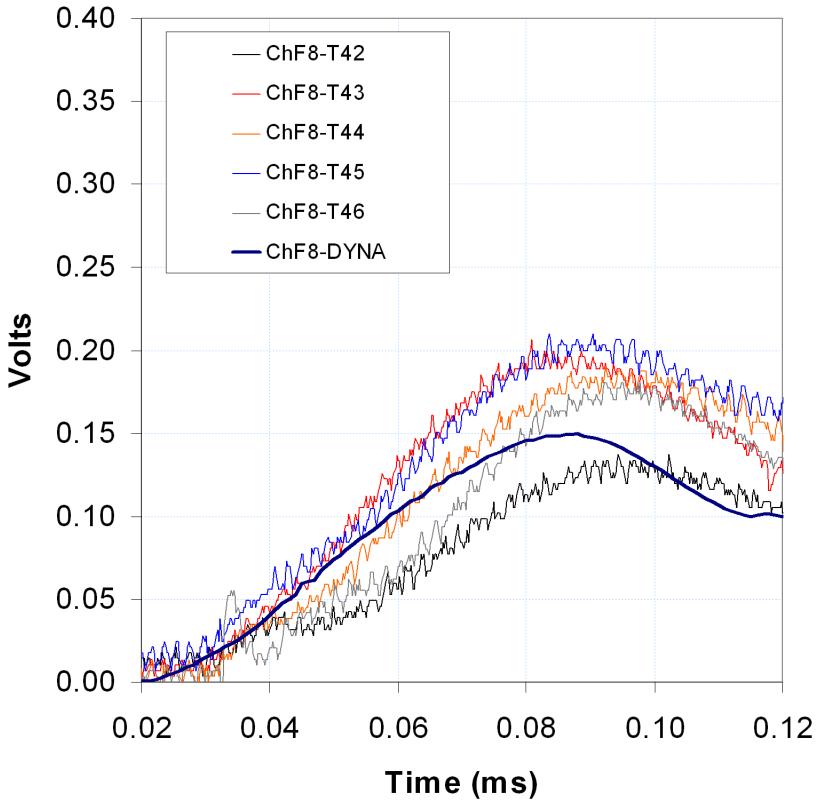


4 cm from impact point

DYNA vs. NiCr wire

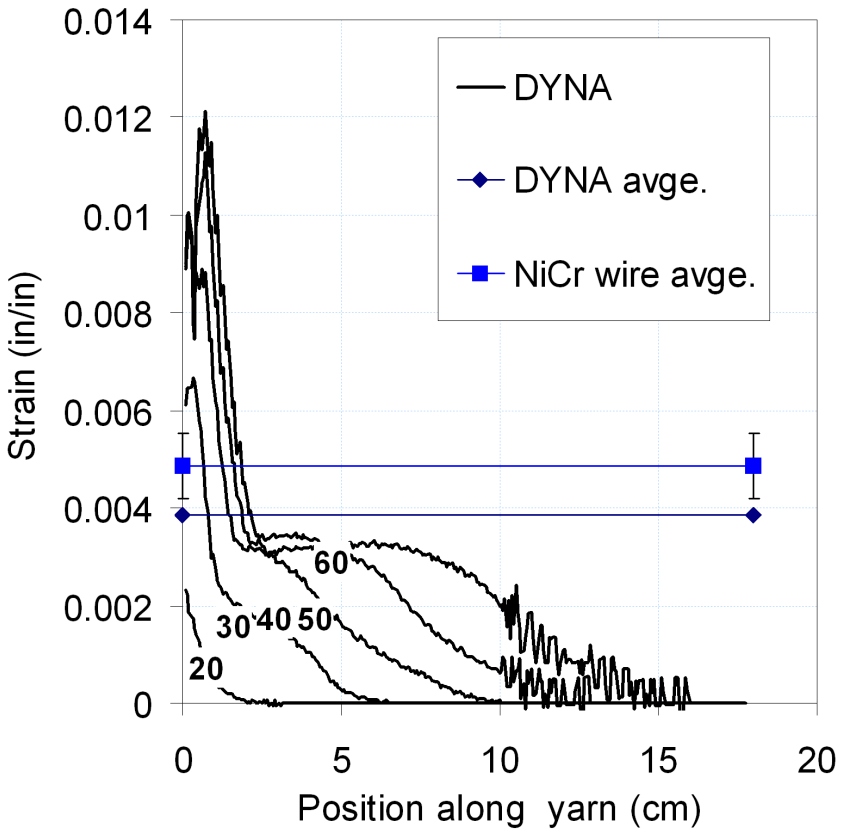


6 cm from impact point

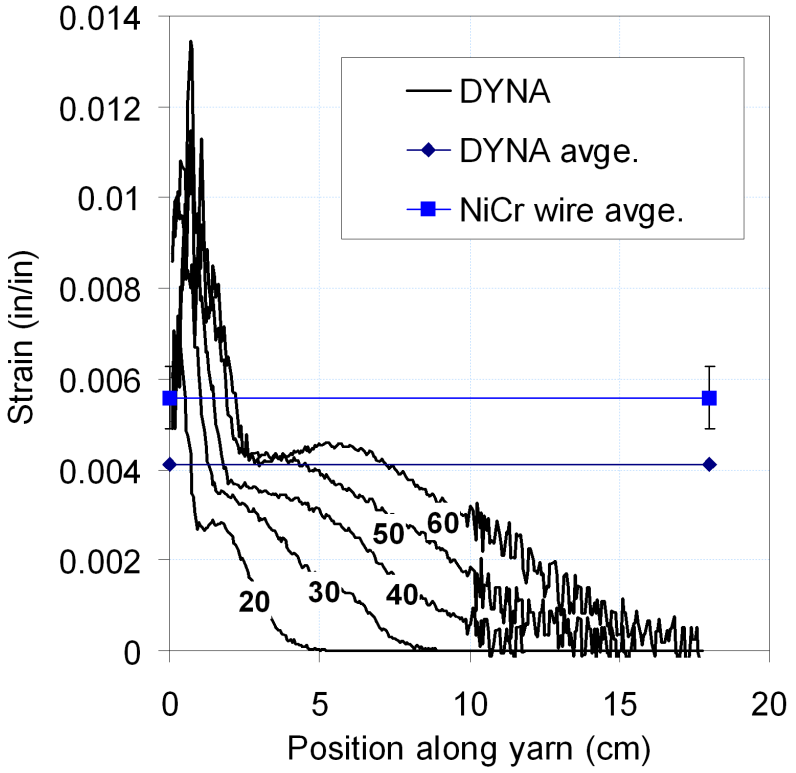


8 cm from impact point

DYNA vs. NiCr wire

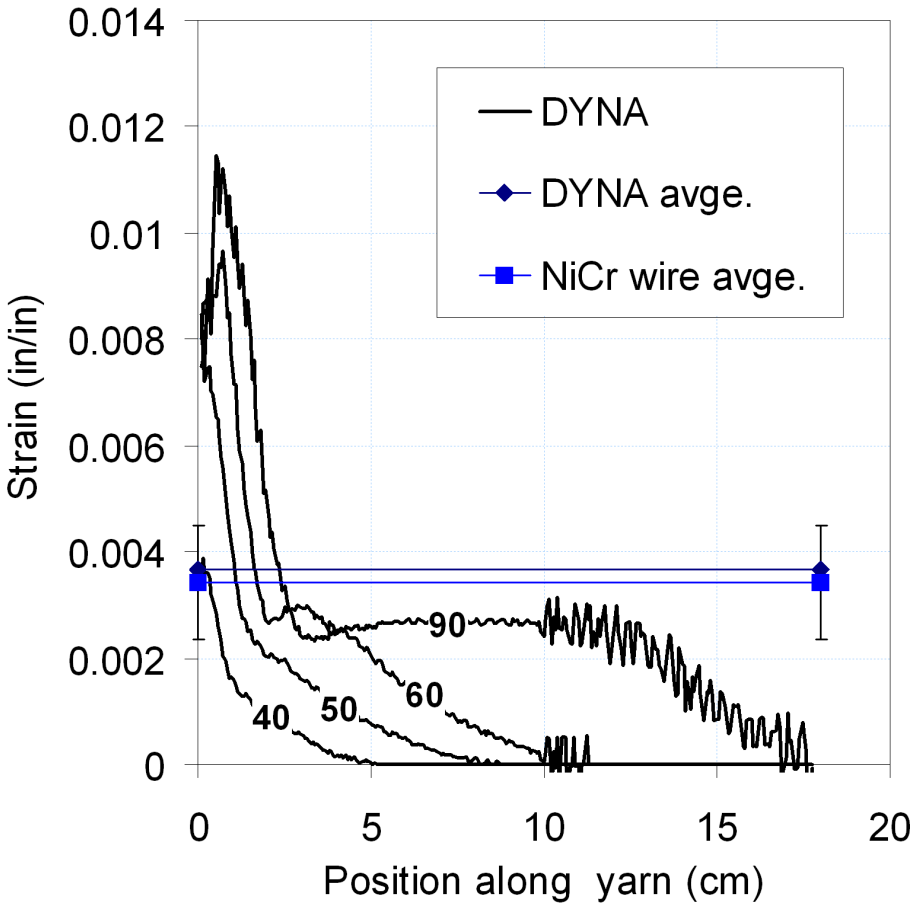


2 cm from impact point

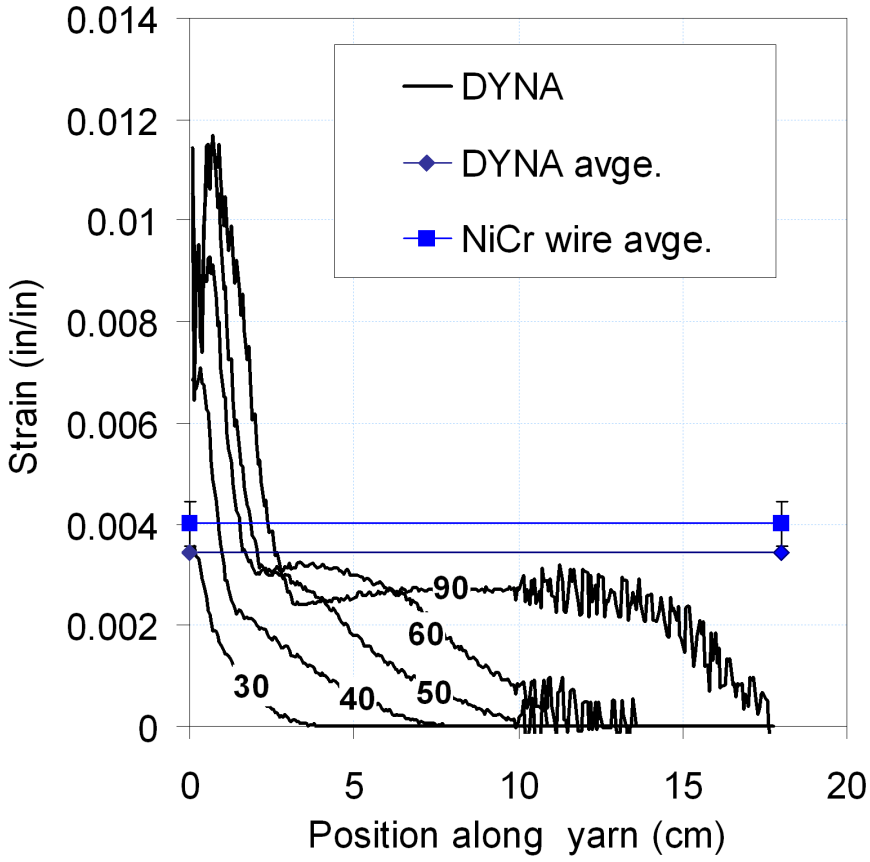


4 cm from impact point

DYNA vs. NiCr wire

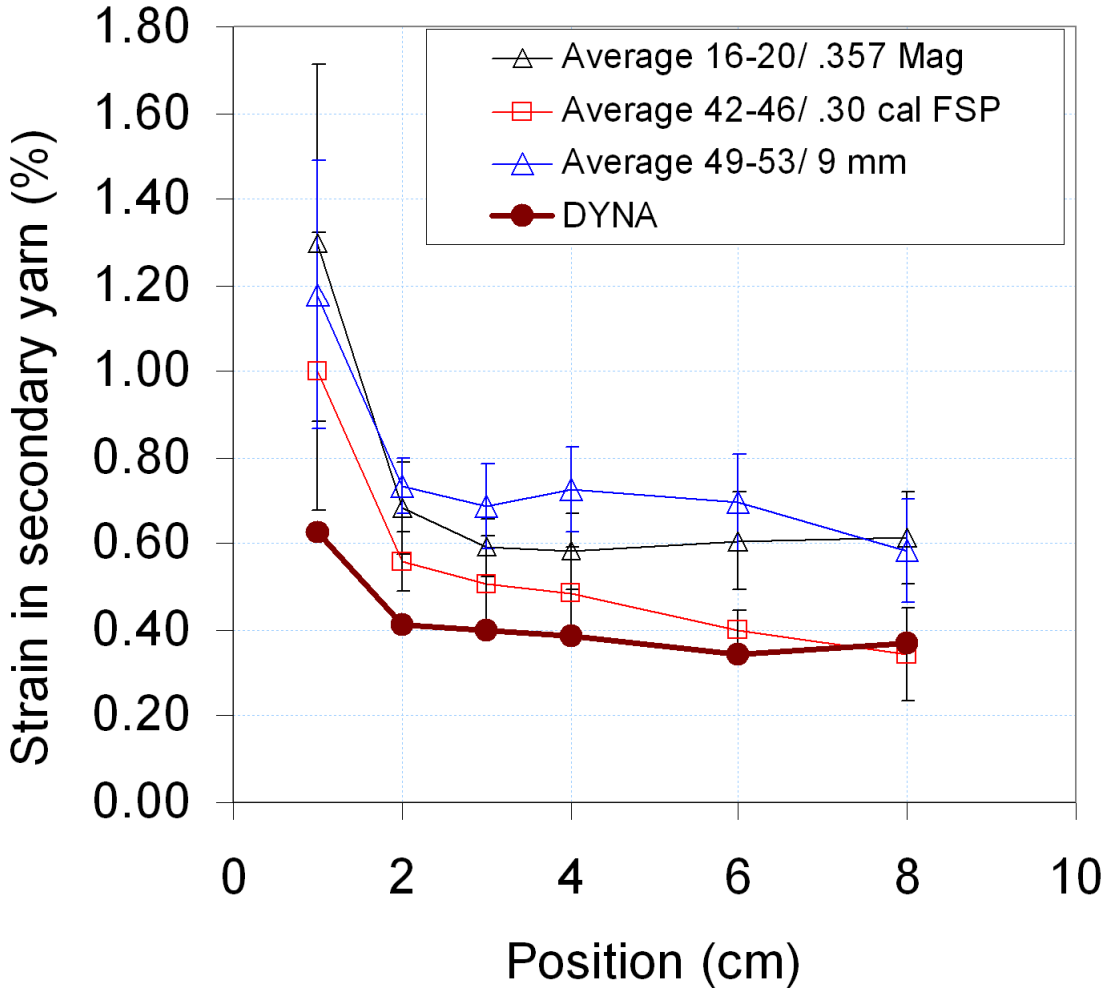


6 cm from impact point

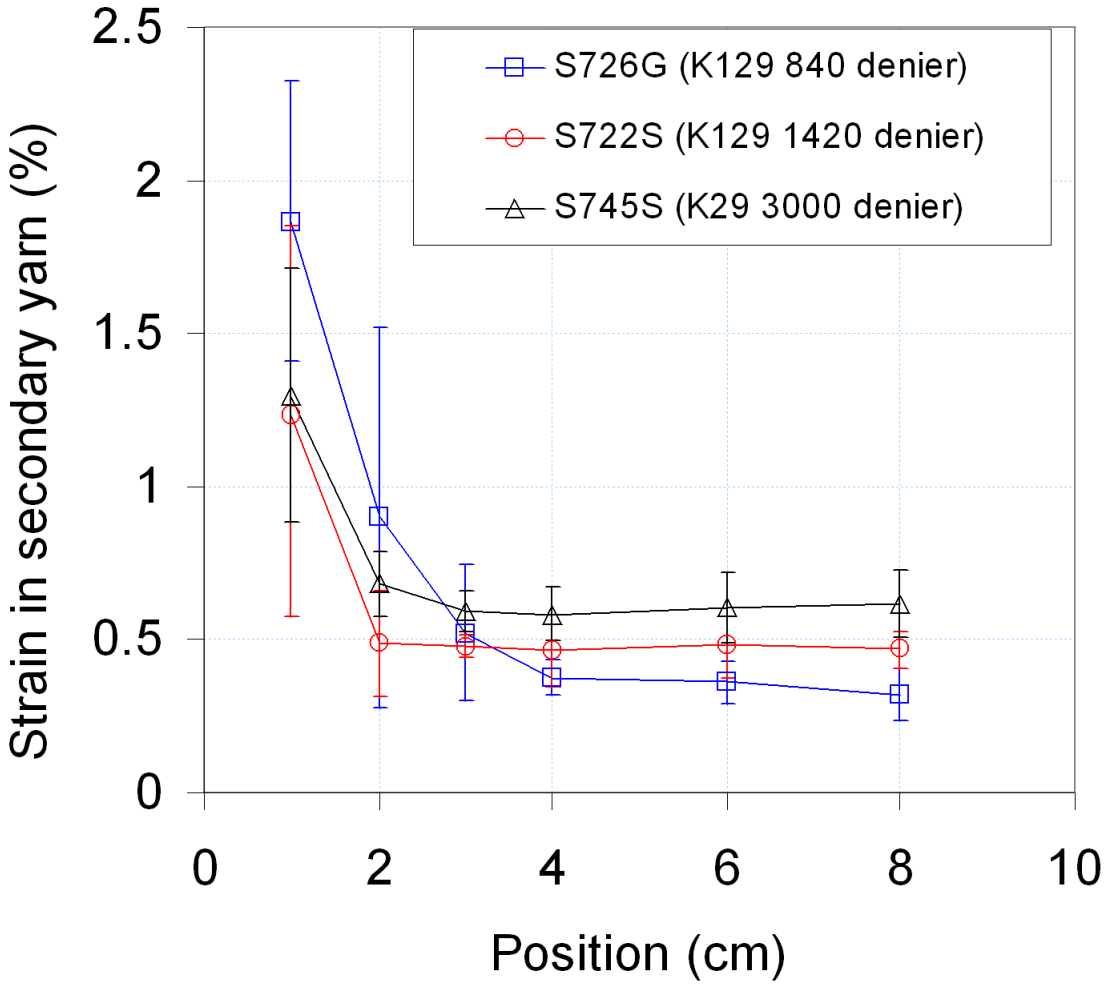
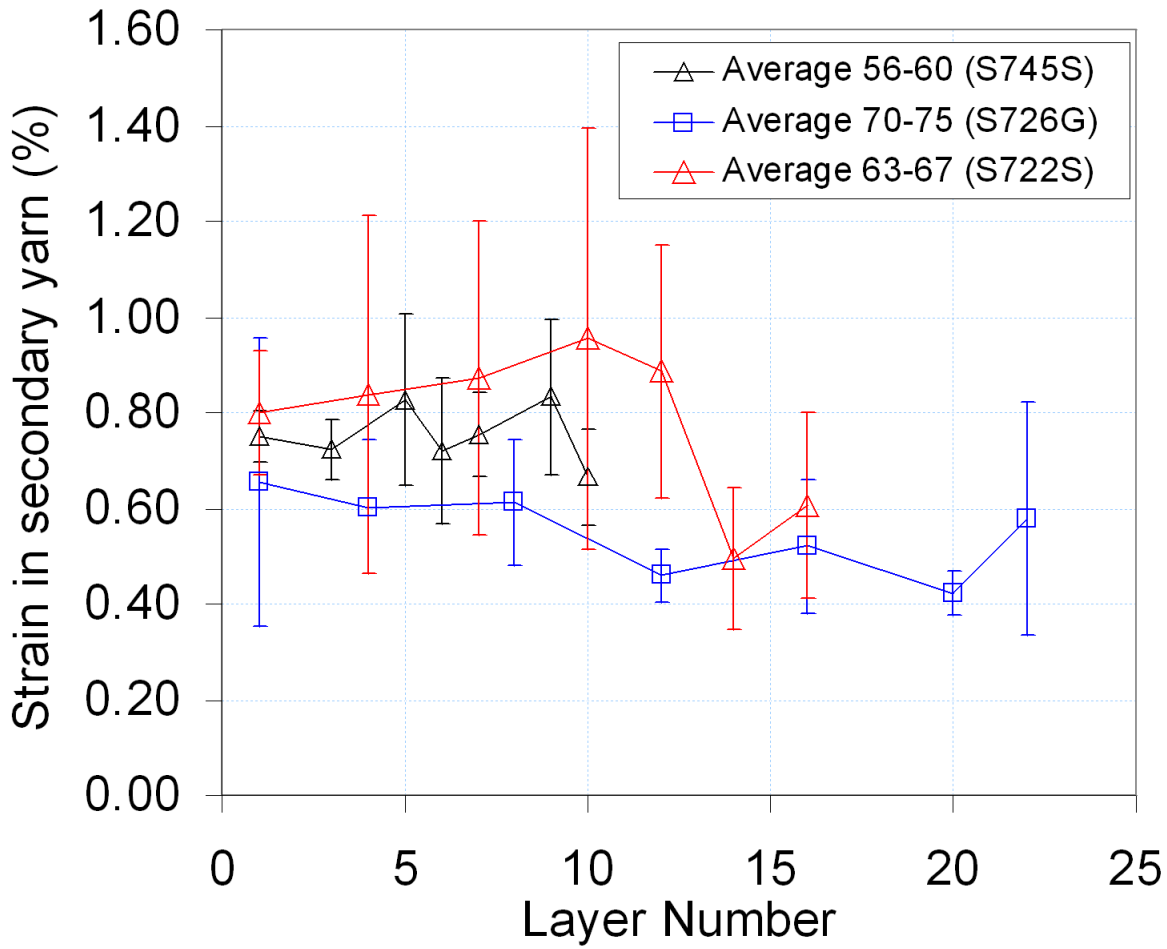


8 cm from impact point

How Strain is Distributed along Fabric NiCr wire and DYNA



How Strain is Distributed along Fabric NiCr wire



How Strain Distributes from Layer to Layer NiCr wire results